

Air–Sea Interaction and the Seasonal Cycle of the Subtropical Anticyclones*

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ABSTRACT

The causes of the seasonal cycles of the subtropical anticyclones, and the associated zonal asymmetries of sea surface temperature (SST) across the subtropical oceans, are examined. In all basins the cool waters in the east and warm waters in the west are sustained by a mix of atmosphere and ocean processes. When the anticyclones are best developed, during local summer, subsidence and equatorward advection on the eastern flanks of the anticyclones cool SSTs, while poleward flow on the western flanks warms SSTs. During local winter the SST asymmetry across the subtropical North Atlantic and North Pacific is maintained by warm water advection in the western boundary currents that offsets the large extraction of heat by advection of cold, dry air of the continents and by transient eddies. In the Southern Hemisphere ocean processes are equally important in cooling the eastern oceans by upwelling and advection during local winter. Ocean dynamics are important in amplifying the SST asymmetry, as experiments with general circulation models show. This amplification has little impact on the seasonal cycle of the anticyclones in the Northern Hemisphere, strengthens the anticyclones in the Southern Hemisphere, and helps position the anticyclones over the eastern basins in both hemispheres. Experiments with an idealized model are used to suggest that the subtropical anticyclones arise fundamentally as a response to monsoonal heating over land but need further amplification to bring them up to observed strength. The amplification is provided by local air–sea interaction. The SST asymmetry, generated through local air–sea interaction by the weak anticyclones forced by heating over land, stabilizes the atmosphere to deep convection in the east and destabilizes it in the west. Convection spreads from the land regions to the adjacent regions of the western subtropical oceans, and the enhanced zonal asymmetry of atmospheric heating strengthens the subtropical anticyclones.

1. Introduction

In passing from Northern Hemisphere winter to summer the low-level atmospheric circulation undergoes a dramatic transition. In Fig. 1 we show seasonal maps

of the sea level pressure and surface winds taken from National Centers For Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses (Kalnay et al. 1996; Kistler et al. 2001). In Fig. 2 we show seasonal maps of the precipitation (Xie and Arkin 1996) and NCEP–NCAR reanalysis subsidence at 700 mb. In the winter the Northern Hemisphere low-level circulation is dominated by lows over the mid-latitude oceans while the subtropical anticyclones are weak and zonally elongated features. By early summer, precipitation is extensive over southeastern Asia and subtropical North America, the lows have almost disappeared, and the subtropical anticyclones now occupy

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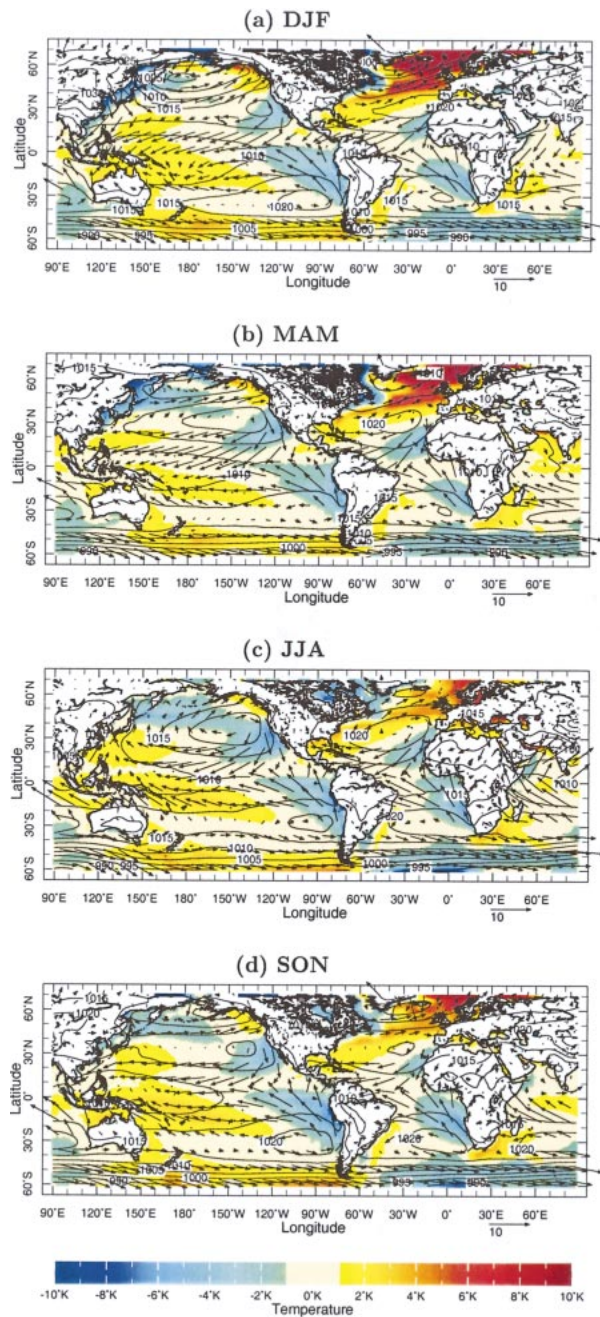


FIG. 1. Sea level pressure (mb), surface winds, and the departure from the zonal mean of sea surface temperature ($^{\circ}\text{C}$) for (a) Dec–Feb, (b) Mar–May, (c) Jun–Aug, and (d) Sep–Nov, from NCEP–NCAR reanalysis.

almost all of the Northern Hemisphere oceans. Strong meridional, equatorward, flow occurs on the eastern flank of the anticyclones and underlies strong subsidence. There is more diffuse southerly flow on the western flank and weak ascent. These arrangements are in accord with Sverdrup balance $\beta v = f\omega_p$, where v is the meridional flow, ω is the vertical velocity in pressure p coordinates and β and f have their usual meaning (Rod-

well and Hoskins 2001, hereafter RH). Northeasterly trade wind flow on the southern flanks, and weak mid-latitude westerlies complete the circulation cells. As the seasonal transition occurs, the difference between the sea surface temperatures (SSTs) of the eastern and western subtropical oceans strengthens. This is also shown in Fig. 1. In winter the eastern oceans are cooler than the west by only about 3°C but in summer this difference grows to as much as 6°C . The cool waters in the east are reflected in lower surface air temperature and specific humidity resulting in strong moist static stability (Fig. 3) ensuring that convection will be shallow.

The seasonal cycle in the Southern Hemisphere has interesting similarities and differences with that in the north. In the Southern Hemisphere, which is mostly ocean, the subtropical surface pressure over the ocean maximizes at the end of winter when the Hadley cell and midlatitude westerlies are at their strongest. In the Northern Hemisphere maximum sea level pressure over the oceans occurs in summer due to the seasonal exchange of mass between the Asian continent and the oceans caused by the massive Asian monsoon. However, as in the Northern Hemisphere, the Southern Hemisphere subtropical anticyclones are best developed as circulation cells (that is the departure from zonal symmetry is most pronounced) during the local spring and early summer season (September–January), similar to the Northern Hemisphere timing. At this time there is extensive precipitation over South America and Africa south of the equator (Fig. 2). In contrast, the zonal asymmetry of SST in the Southern Hemisphere is strongest during spring and actually weakens from spring to summer. These different seasonal cycles of SST and the subtropical anticyclones suggest that the balance of processes linking the oceans and the subtropical anticyclones must be different in the two hemispheres.

The seasonal cycle of SST asymmetry can be influenced by a number of processes. When the anticyclones are most developed, the eastern subtropical oceans experience equatorward flowing winds and subsidence, the western oceans poleward flowing winds and ascent. There is general equatorward flow in the ocean, and strong coastal upwelling in the east and a poleward, westward-intensified, boundary current in the west. There is also extensive boundary layer cloud cover (closely linked to the strong moist static stability shown in Fig. 3), which has a net cooling effect on climate (Hartman et al. 1992; Klein and Hartmann 1993), in the east but not in the west. Each of the processes could create the SST asymmetry but their relative contributions are not known. Further, each of them will tend to increase the asymmetry year-round; so what process weakens the asymmetry (i.e., cools the west relative to the east) as the anticyclones weaken?

The mechanisms that underlie the development and maintenance of the subtropical anticyclones are still in dispute. First of all, the mountains of the Americas can split the subtropical high pressure belt into cells over

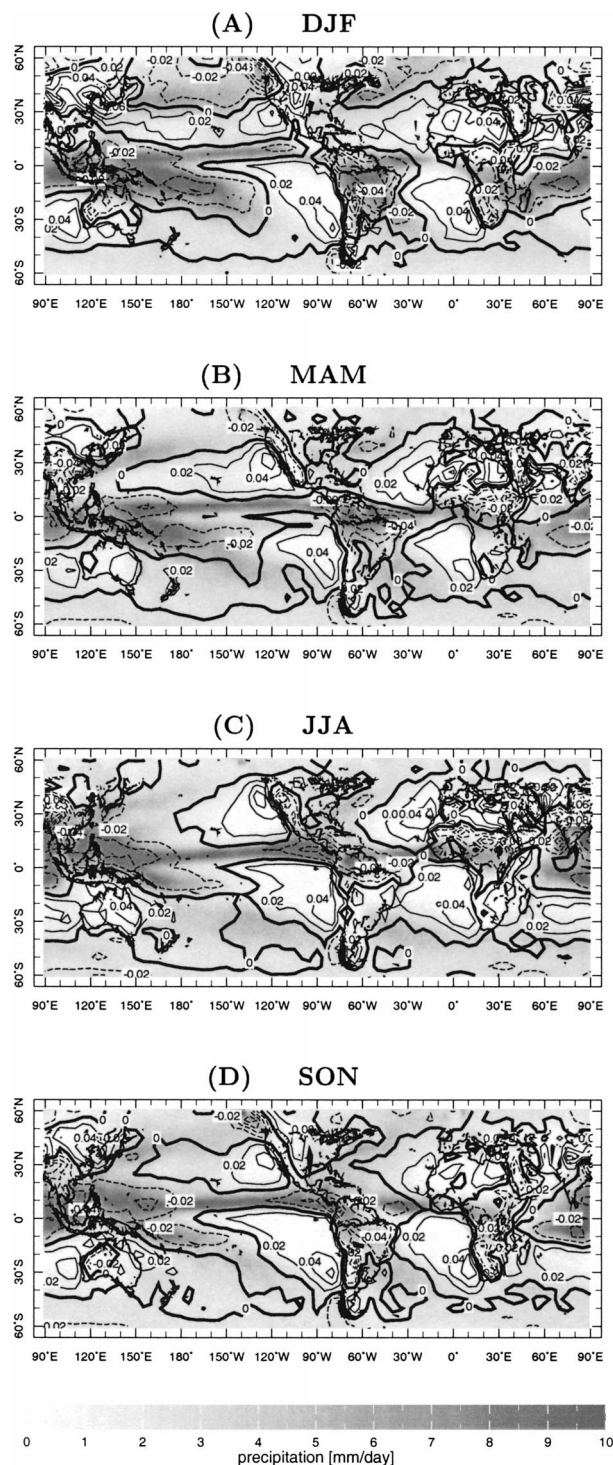


FIG. 2. Precipitation (mm day^{-1}) and subsidence (Pa s^{-1}) for (a) Dec–Feb, (b) Mar–May, (c) Jun–Aug, and (d) Sep–Nov. The precipitation is from Xie and Arkin (1996) and the subsidence is from NCEP–NCAR reanalysis.

the ocean as shown in RH. The orographically forced cells are weak, and RH suggest that the Pacific anticyclones develop strength as a remote response to summer convection over the Americas. They also show that the Kelvin wave forced by heating in the Asian monsoon is important in forcing the equatorial, trade wind, part of both the North Pacific and North Atlantic anticyclones. Ting (1994) and Chen et al. (2001) have also argued that the northern summer anticyclones are forced by the Asian monsoon heating, while heating in the region of the Americas (e.g., see Fig. 2) simply breaks the high into two cells.

However, as RH show, the summer anticyclones forced remotely by monsoonal heating are weak compared to observations. To bring them up to observed strength they appeal to “diabatic amplification.” Forced descent creates a warm anomaly, enhanced radiative cooling and, therefore, enhanced descent that inhibits convection and latent heat release. However, NCEP–NCAR reanalysis data show that the atmosphere is actually slightly cooler in the regions of descent than in the regions of ascent. The low levels of atmospheric moisture in the descent regions should also weaken the radiative cooling rates. Bergman and Hendon (2000) have shown that clouds reduce radiative cooling in regions of deep convection, enhance radiative cooling in regions of shallow convection, and amplify the circulation forced by condensational heating—providing an alternative mechanism for diabatic amplification. Liu et al. (2001) emphasize the role of surface sensible heating of the atmosphere in summer over the Tibetan Plateau for the enhancement of the North Pacific anticyclone. In the current paper we examine whether local air–sea interactions and ocean dynamics influence the development and maintenance of the subtropical anticyclones.

We will address the following questions:

- What atmospheric mechanisms influence the development of the zonal asymmetries of SST across the subtropical oceans and their seasonal cycle? Contenders are horizontal advection and subsidence by the mean flow, transient eddy fluxes, and cloud radiative feedbacks, but what are the relative importance of these processes?
- How important is ocean heat transport in explaining the zonal asymmetry of SST and its seasonal cycle? Would the seasonal cycles of the subtropical anticyclones and their strength be different if the ocean heat transport was absent?
- To what extent can the subtropical anticyclones be understood as the remote response to monsoonal heating over land with the SST asymmetry arising as a response, or does the SST asymmetry subsequently impact the atmospheric circulation?
- Can air–sea interaction provide a mechanism whereby the atmospheric circulation, initially forced remotely by convective heating over land, creates zonal asymmetries of SST that favor precipitation over the western subtropical oceans that amplifies the initial circulation?

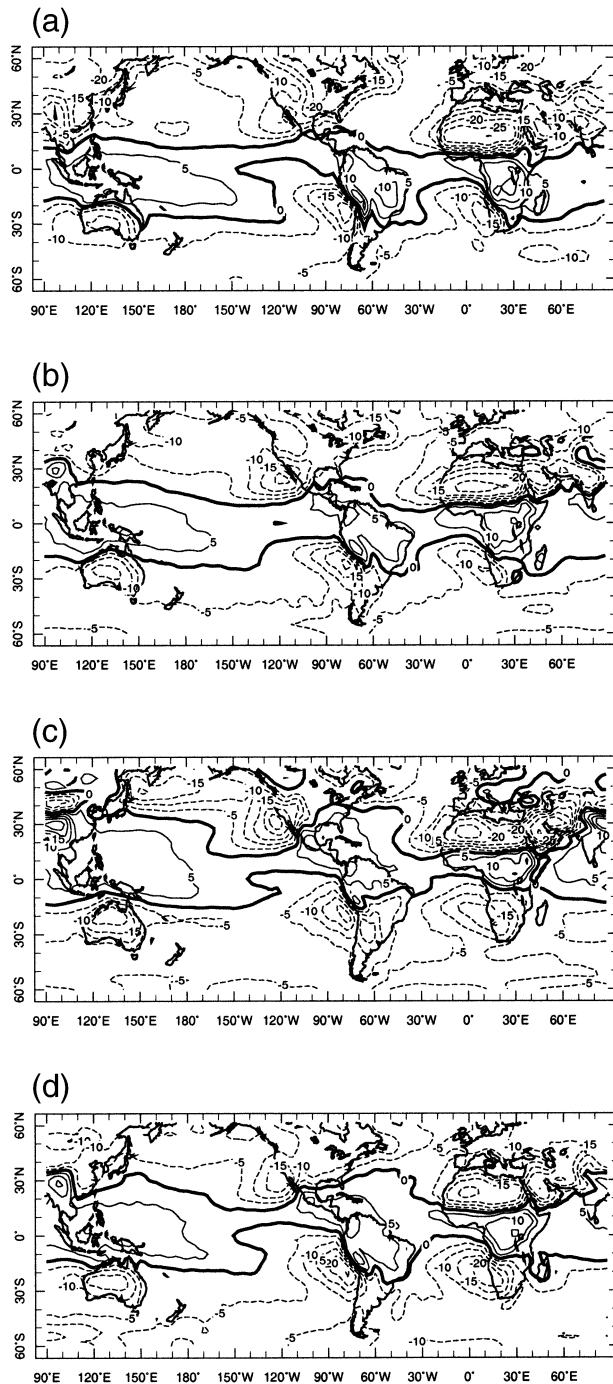


FIG. 3. The moist static instability, defined as the moist static energy at 1000 mb minus the saturation moist static energy at 700 mb for (a) Dec–Feb, (b) Mar–May, (c) Jun–Aug, and (d) Sep–Nov. The data are from NCEP–NCAR reanalysis. Units are 10^3 J kg^{-1} .

In section 2 we describe the datasets and models used. Then, in section 3, we present an observational analysis of the atmospheric processes that can create the zonal asymmetries of SST. The ocean processes that influence the SST—advection and mixing—are derived from

wind-forced simulations with ocean GCMs. This analysis will reveal the relative importance of mean horizontal advection of heat and moisture, mean subsidence warming and drying, transient eddy fluxes, cloud–radiation interactions, and ocean heat transport in establishing the asymmetries of SST.

In section 4, we examine simulations conducted with atmospheric general circulation models (GCMs) coupled to mixed layer oceans to argue that the anticyclones are only modestly influenced by the ocean heat transport but that the SST asymmetry is strongly influenced. In section 5 we use an idealized atmosphere–ocean model to test this hypothesis. In section 6 we propose a theory for the seasonal cycle of the subtropical anticyclones and associated zonal asymmetries of SST. Conclusions are offered in section 7.

2. Observational datasets and models

a. Atmospheric datasets

The NCEP–NCAR reanalysis data from 1949 to 2001 (Kalnay et al. 1996; Kistler et al. 2001) are used to derive estimates of the mean horizontal and vertical advection and the transient eddy divergence of moist static energy. Values of temperature, specific humidity, geopotential, and zonal and meridional winds are used at levels from 700 to 1000 mb. The reanalysis is also used for the sea level pressure and the SST. The reanalysis cloud cover is poor, when compared to ship or satellite observations, over the eastern subtropical oceans. This primarily affects the surface solar radiation, so for that we turn to satellite data but use NCEP–NCAR data for the surface longwave radiation.

b. Surface solar radiation

The surface solar radiation is taken from Earth Radiation Budget Experiment (ERBE) data (1985–1989) derived from satellite observations (Li and Leighton 1993). Estimates of the surface solar radiation from ERBE data are very similar to those from the independent International Satellite Cloud Climatology Project (ISCCP) data (Bishop and Rossow 1991) except for a simple offset (Seager and Blumenthal 1994). Here we will only show results using the ERBE data.

c. Ocean GCMs

To derive estimates of the changes in SST due to ocean advection and mixing two wind-driven ocean GCMs are used. For the Northern Hemisphere we use the Lamont Ocean–Atmospheric Mixed Layer Model (LOAM). The model has been described by Visbeck et al. (1998). For the Pacific the configuration is described by Seager et al. (2001) and for the Atlantic by Seager et al. (2000). The model extends to 40°S with meridional resolution varying from 0.5° near the equator to 2° in

midlatitudes and a fixed 2° resolution in longitude. Vertical resolution is concentrated in the upper 300 m with fewer than ten levels below. The model includes basin geometry and bathymetry consistent with the resolution. Temperature and salinity are restored to climatology at the southern boundary. The model includes a bulk wind-driven mixed layer model, convective adjustment and isopycnal thickness diffusion. In this model the mixed layer can contain several model levels.

LOAM performs poorly in the southeastern South Pacific. Instead, for both the South Pacific and the South Atlantic, we use the layer model of Murtugudde et al. (1996). This ocean GCM is a reduced-gravity, primitive equation, sigma-coordinate model (Gent and Cane 1989) with an embedded hybrid mixing scheme (Chen et al. 1994). The model has a mixed layer and 19 layers below with the highest vertical resolution immediately below the mixed layer. The motionless deep layer is at 6°C and 35 psu for the Atlantic and at 4°C and 35 psu for the Pacific. The model domain for the Atlantic covers 40°S – 40°N and 45°S – 65°N for the Pacific. For both basins the meridional resolution is 0.5° but 0.33° in the 10°S – 10°N band and 0.66° in longitude.

Both ocean GCMs are coupled to the advective atmospheric mixed layer (AML) model of Seager et al. (1995). The AML model computes the air temperature and air humidity together with the surface fluxes of latent and sensible heat and longwave radiation, using the modeled SST and the observed wind speed and direction. This methodology takes proper account of the thermodynamic coupling between the atmosphere and ocean that underlies how the SST is determined.

The ocean GCMs are forced by observed wind stresses, wind speeds and directions. For the North Pacific these are taken from daSilva et al. (1994), but elsewhere they are taken from NCEP–NCAR reanalyses. The ocean GCMs also need the surface solar radiation, which is taken from ERBE or ISCCP, corrected to remove the mean offset between them (see Seager and Blumenthal 1994).

d. Idealized atmosphere–ocean model

An idealized atmospheric GCM is used to model the atmospheric circulation variously forced by imposed heating over land and sea. The dynamical core of the model is based on the Geophysical Fluid Dynamics Laboratory (GFDL) GCM. The model has rhomboidal truncation at zonal wavenumber 20 and 11 vertical layers and contains orography. The circulation is forced by relaxation of the model temperature to the reference state of Held and Suarez (1994) plus specified heating. The vertical integral of the specified heating is equal to the latent heat released by condensation as estimated from the precipitation data of Xie and Arkin (1996). Dissipation is provided by a ∇^4 diffusion, which damps the highest resolved wavenumber on a 2-day timescale. There is also a vertical momentum diffusion and friction in the lowest layer that damps with a 0.5-day timescale.

The specific humidity, which does not feed back onto the specified condensational heating, is computed accounting for advection and using simple parameterizations of evaporation and rainout.

The atmosphere model forces a 50-m-deep mixed layer ocean model. The zonal mean SST in the mixed layer remains specified. Zonal deviations are computed in terms of the zonal deviation of the latent plus sensible heat flux (surface radiation is assumed to be zonally symmetric). The sensible and latent heat fluxes are computed by bulk formulas using the air temperature and humidity modeled by the atmospheric GCM. Deviations of SST from zonal symmetry in this model can only arise due to advection within the atmospheric circulation (mean plus transient) forced by imposed heating.

e. Climate models

Two different climate models were used. Each is an atmospheric GCM (AGCM) coupled to a mixed layer ocean. One AGCM is the Goddard Institute for Space Studies (GISS) model (Hansen et al. 1984; Del Genio et al. 1996), a gridpoint model with $4^\circ \times 5^\circ$ resolution and nine vertical levels. The other model is the NCAR Community Climate Model 3 (CCM3; Kiehl et al. 1998) run with triangular truncation at zonal wavenumber 42 and 18 vertical levels. The GISS model is coupled to a mixed layer ocean whose depth varies in a specified way both seasonally and spatially (Russell et al. 1985), while the CCM3 is coupled to a mixed layer of uniform 50-m depth. In each climate model the mixed layer contains a specified “ q -flux” constructed so that, when coupled, the model reproduces the observed SST with reasonable fidelity. The q -flux accounts for the movement of heat by the ocean as well as for errors in the model’s surface heat fluxes. In the case of CCM3, with a fixed mixed layer depth, the q -flux also implicitly accounts for the exchange of heat between the mixed layer and water below but this is explicitly computed within the GISS model where the mixed layer depth varies. In companion experiments the q -flux was set to zero so that the SST was determined by a local balance of surface fluxes and SST tendency. The runs with a zero q -flux allow us to see the impact of the ocean heat transport on the seasonal cycle of subtropical SSTs and the subtropical anticyclones.

Both GCMs seriously underestimate boundary layer cloud cover over the eastern oceans. Their radiative impact on the SSTs is therefore included with the ocean heat transport (OHT) in the specified q -flux. Setting the q -flux to zero therefore also removes the radiative impact of boundary layer clouds.

3. Observational analysis of subtropical air–sea interaction

a. Basic concepts and equations

The SST is determined by a balance of horizontal and vertical ocean advection, vertical ocean mixing, and the

net surface heat flux. The surface fluxes of heat, radiation, and moisture are balanced within the atmosphere by advection, subsidence, vertical mixing (or turbulence), and radiation. It is useful to combine the ocean and atmospheric boundary layers, by eliminating the surface fluxes, so we can examine the atmospheric processes that create variations in SST.¹

The SST equation can be written as

$$\rho c_{pw} H \frac{\partial T}{\partial t} = \text{OP} - F_{\text{solar}}^0 - F_{\text{LW}}^0 - F_{\text{SH}}^0 - F_{\text{LH}}^0. \quad (1)$$

Here ρ is the density of water; c_{pw} is its specific heat; H is the mixed layer depth, which varies in space and

time; T is the mixed layer temperature, which equals the SST; OP is the SST tendency due to advection and mixing (see appendix), and the F terms refer to the surface solar (F_{solar}^0) and longwave (F_{LW}^0) radiative fluxes, and the sensible (F_{SH}^0) and latent (F_{LH}^0) heat fluxes. The 0 superscript indicates a surface value. The surface flux terms are defined as positive upward, but OP is defined as positive if it leads to an increase of SST.

The equation for the moist static energy, $h = c_p T_a + gz + Lq$, of the lower levels of the atmosphere, where T_a is the air temperature, z is the geopotential, q is the specific humidity, and L is the latent heat of condensation, is given by

$$\begin{aligned} & \frac{1}{g} \int_{p_t}^{p_0} \left\{ \left(\frac{\bar{u}}{a \cos \phi} \frac{\partial \bar{h}}{\partial \lambda} + \frac{\bar{v}}{a} \frac{\partial \bar{h}}{\partial \phi} + \frac{\bar{\omega}}{\bar{\omega}} \frac{\partial \bar{h}}{\partial p} \right) + \left[\frac{1}{a \cos \phi} \left(\frac{\partial(\overline{u'h'})}{\partial \lambda} + \frac{\partial(\overline{v'h'}) \cos \phi}{\partial \phi} \right) + \frac{\partial(\overline{\omega'h'})}{\partial p} \right] \right\} dp \\ & = \int_{p_t}^{p_0} \left(\frac{\partial F_{\text{RAD}}}{\partial p} + \frac{\partial F_h}{\partial p} \right) dp = F_{\text{solar}}^0 + F_{\text{LW}}^0 + F_{\text{SH}}^0 + F_{\text{LH}}^0 - F_{\text{RAD}}^{p_t} - F_h^{p_t}. \end{aligned} \quad (2)$$

Here c_p is the specific heat for air, λ is longitude, ϕ is latitude, F_{RAD} is the radiative flux, and F_h is the turbulent flux of moist static energy; the overbars denote monthly means and primes denote departures from monthly mean; $F_h^{p_t}$ is the turbulent flux of moist static energy at the top of the layer where the pressure is p_t , and $F_{\text{RAD}}^{p_t}$ is the net radiative flux at this same level. Since the top of the layer is at 700 mb, the boundary layer mixing part of $F_h^{p_t}$ will be small and this term will instead be

dominated by convective mixing between the surface layers and the mid and deep troposphere. The first bracketed term on the left within the square brackets is the advection and subsidence of moist static energy by the mean flow and the second term is the transient eddy flux divergence of moist static energy.

By combining these two equations we derive an equation for the SST in terms of the ocean, atmosphere, and radiative processes that alter it:

$$\begin{aligned} \rho c_{pw} H \frac{\partial T}{\partial t} = \text{OP} - \frac{1}{g} \int_{p_t}^{p_0} \left\{ \left(\frac{\bar{u}}{a \cos \phi} \frac{\partial \bar{h}}{\partial \lambda} + \frac{\bar{v}}{a} \frac{\partial \bar{h}}{\partial \phi} + \frac{\bar{\omega}}{\bar{\omega}} \frac{\partial \bar{h}}{\partial p} \right) \right. \\ \left. + \left[\frac{1}{a \cos \phi} \left(\frac{\partial(\overline{u'h'})}{\partial \lambda} + \frac{\partial(\overline{v'h'}) \cos \phi}{\partial \phi} \right) + \frac{\partial(\overline{\omega'h'})}{\partial p} \right] \right\} dp - F_{\text{RAD}}^0 - \Delta N_T - F_h^{p_t}, \end{aligned} \quad (3)$$

where $\Delta N_T = F_{\text{RAD}}^{p_t} - F_{\text{RAD}}^0$ is the radiative flux divergence across the atmospheric layer and is typically positive.

Of the terms on the right-hand side, the SST tendency due to ocean processes (advection plus mixing), OP, will

be evaluated from wind-forced ocean GCMs (see appendix); the advection by the mean flow and the transient eddy flux divergence will be evaluated from NCEP–NCAR reanalyses; and the net radiation at the ocean surface, F_{RAD}^0 , will be taken from ERBE for the solar component and NCEP–NCAR reanalyses for the longwave component. The SST is taken from NCEP–NCAR reanalyses. Neither the radiative cooling of the lower levels of the atmosphere, ΔN_T , nor the convective mixing at the top of the level, $F_h^{p_t}$, can be directly evaluated from the data. Here, they are instead evaluated as a residual from Eq. (3). The residual term also includes within it errors in the observational data and the model

¹ Looking at the surface fluxes alone can be misleading. For example the cool eastern subtropical oceans are places where the surface heat loss from the ocean is no larger than at other longitudes at the same latitude. It might therefore be thought that atmospheric processes are not creating the cold SSTs, but instead, as atmospheric advection and subsidence cool the SST, and cloud cover reduces the incoming solar radiation, the latent heat loss becomes less to restore a balance with close to zero net surface heat flux (Blumenthal 1990).

diagnosis of OP. Although it includes all the error, the spatial distribution of the residual is much as expected. It is a cooling term for the SST essentially everywhere, increasing from about 50 W m^{-2} in the extratropics to near 100 W m^{-2} in the deep Tropics [consistent with the expected values of boundary layer radiative flux divergence (Betts and Ridgway 1989)], and can reach 200 W m^{-2} in the intertropical convergence zone where convective turbulent mixing of moist static energy is large.

b. Climatological air–sea interaction during summer and winter

Figure 4 shows the SST tendencies in December–February (DJF), in W m^{-2} , due to each atmospheric or oceanic process. Figure 5 shows the same quantities for JJA.

In the subtropical Northern Hemisphere during winter the SST tendency due to mean advection and subsidence (Fig. 4a) cools the SST across the subtropical oceans. This reflects the zonally symmetric wintertime Hadley cell. Outflow of cold, dry air from Asia and North America further cools the western oceans. In contrast, during summer (Fig. 5a) the mean circulation warms the western subtropical oceans and cools the eastern oceans. This reflects both the direction of horizontal flow around the subtropical anticyclones and the localization of the descent in the east. In the east the vertical term is dominant and the subsidence warming part ($\sim 70 \text{ W m}^{-2}$) is closely balanced by radiative cooling (Betts and Ridgway 1989). The subsidence drying part is larger ($\sim 130 \text{ W m}^{-2}$) and is balanced by evaporation, which cools the SST. The transient eddy moist static energy divergence (Figs. 4b and 5b) cools the subtropical SSTs throughout the year but by more in winter than summer and by more in the west than in the east.

The SST tendencies due to mean circulation and transients in the Southern Hemisphere have similar relationships to local season as in the Northern Hemisphere. The creation of the zonal asymmetry of SSTs by the mean flow is most obvious in local summer in the South Pacific (Fig. 4a). In the South Atlantic the mean circulation cools most in the central ocean. Transients cool both subtropical oceans throughout the year and by more in winter than summer, but the east to west difference in their effect is much smaller than in the north due to the lack of marked continentality.

In the northern subtropics ocean processes (Figs. 4c and 5c)² warm the west during winter and cool the east during summer. Both features are more confined to the coast than either the SST tendencies due to the atmospheric circulation or the basin-scale features of the SST asymmetry itself. However, in the Southern Hemisphere, cooling by ocean processes extends considerably

farther west from the coast. The warming in the west is less strong than in the Northern Hemisphere, presumably due to the weaker western boundary currents.

The net solar radiation absorbed by the ocean is quite zonally uniform during Northern Hemisphere winter. At other times, and in the Southern Hemisphere throughout the year, the eastern subtropical oceans get less radiation than areas to the west due to local maxima of low-level cloud cover (Klein and Hartmann 1993), but these features are confined near the coast.

c. Causes of the seasonal cycle of SST asymmetry across the subtropical oceans

In Figs. 6 through 9 we plot the seasonal evolution of the SST and the terms on the right-hand side of Eq. (3), that is, the terms determining the SST, as a function of longitude. All quantities have been averaged over 15° – 35°N in the Northern Hemisphere and 25° – 5°S in the Southern Hemisphere. The southern latitude band is chosen to be closer to the equator than the northern band to reflect the fact that the latitude of maximum SST asymmetry is also nearer the equator. All of the terms are plotted as the departure from the zonal mean of the appropriate ocean basin. This allows us to look directly at the zonal asymmetry. Positive values indicates a warming tendency. Figure 6 is for the North Pacific, Fig. 7 for the North Atlantic, Fig. 8 for the South Pacific, and Fig. 9 for the South Atlantic.

1) THE NORTHERN HEMISPHERE

In the North Pacific and North Atlantic the SST asymmetry (Figs. 6a and 7a) has a maximum in August and a minimum in February. The seasonal cycle of the mean advection of moist static energy is the most obvious cause (Figs. 6b and 7b): strong cooling in the east and warming in the west during April–July precedes the maximum of the SST asymmetry. Once the SST asymmetry has reached its full value, the generation of the asymmetry by the mean advection has weakened. Shortly afterward, in the fall, the mean advection begins to cool the west of the Pacific Ocean, but this effect is weak in the Atlantic. The winter mean advective cooling of the west is caused by the strengthening and southward shift of the midlatitude westerlies and the advection of cold dry air off the continents. Transient eddies (Figs. 6c and 7c) assist the winter cooling of the western oceans relative to the east. Consequently the atmospheric circulation, mean plus transient, creates the fundamentals of the seasonal cycle of the asymmetry of SST: mean advection strengthens the asymmetry from spring to summer and both the mean advection and transients weaken the asymmetry from fall through the winter. The wintertime weakening is almost strong enough that it would eliminate the SST asymmetry if it was unopposed.

The net surface radiation is shown in Figs. 6d and

² Note that we have not simulated the Indian Ocean and its area is left blank in these figures.

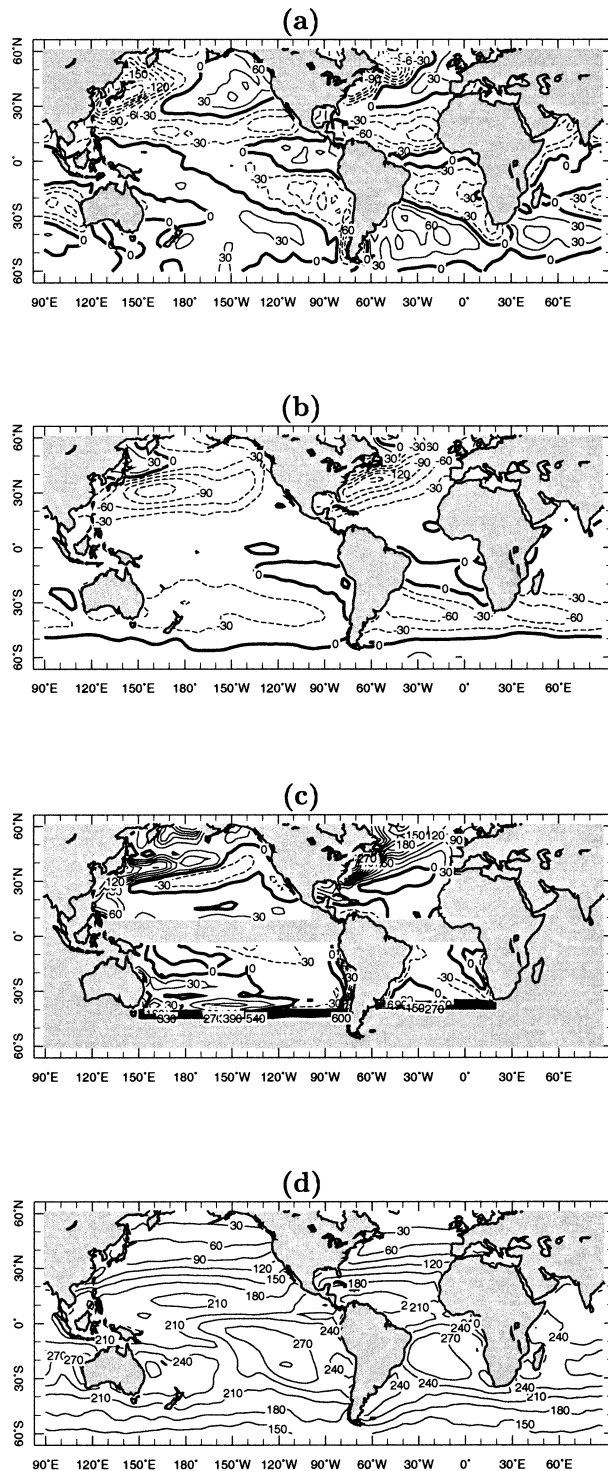


FIG. 4. (a) The mean advection of moist static energy, (b) transient moist static energy flux divergence, (c) the sum of ocean advection and mixing (equatorial region where the two ocean models meet, and where values are very large, is masked out), and (d) the net surface solar radiation for Dec–Feb. The advection and transient flux divergence are evaluated from NCEP–NCAR reanalysis, the ocean processes tendency from the ocean GCM, and the net surface solar radiation from ERBE. All terms are plotted as positive if they tend to increase the SST and are in W m^{-2} .

7d. Cloud–radiation interactions only have a modest impact on the seasonal cycle of the asymmetry and are particularly weak over the Atlantic Ocean where summertime cloud cover is less than over the North Pacific (Klein and Hartmann 1993). The timing is consistent with the change in boundary layer clouds being a positive feedback: the atmospheric circulation creates cool SSTs in the east and increases the static stability (see Fig. 3), which in turn increases the boundary layer cloud cover causing further cooling of the SST. This amplifies the SST asymmetry but only immediately west of the American and African coasts.

Cooling of the eastern oceans by advection and mixing in the ocean is also quite confined to the eastern coast (Figs. 6e and 7e). More important is the large warming in the west during winter. This is primarily a result of the ocean mixed layer deepening, as it is cooled by strong surface heat loss sustained by cold, dry advection and atmospheric transient eddy fluxes, and entraining warmer waters from below. The temperatures of the waters below are themselves sustained by horizontal advection in the western boundary current. These ocean processes oppose the cooling by the mean and transient atmospheric circulation allowing the SST asymmetry to persist year-round. In its absence we would expect the SST asymmetry to be much weaker.

The residual, the sum of radiative cooling of the boundary layer and the turbulent flux of moist static energy at its top (plus error), is shown in Figs. 6f and 7f. We expect the boundary layer radiative cooling to be larger (on the order of 20 W m^{-2}) in the west than in the east because of the greater water vapor content (Betts and Ridgway 1989). This term contains the positive water vapor greenhouse feedback on the SST and will enhance the SST asymmetry by increasing the downward longwave flux in the west. However, the asymmetry of the turbulent flux at the top of the layer is probably larger. As the western oceans warm in summer deep convection occurs and fluxes moist static energy upward. In the east, convection is suppressed by the stable boundary layer. Hence the turbulent flux damps the SST asymmetry in the late summer season.³

2) THE SOUTHERN HEMISPHERE

In the Southern Hemisphere the SST asymmetry is strongest in October–December and weakest in March (Figs. 8a and 9a). Throughout the Southern Hemisphere winter the SST asymmetry is strengthening, in contrast to the Northern Hemisphere during winter when the asymmetry weakens. This difference seems to be a result

³ The apparent maintenance of the SST asymmetry by the residual term in the North Pacific (and to a lesser extent in the North Atlantic) during winter almost certainly indicates error. Most likely it is attempting to account for underestimation of the warming in the west by advection in the western boundary currents caused by the modest horizontal resolution in the ocean GCM.

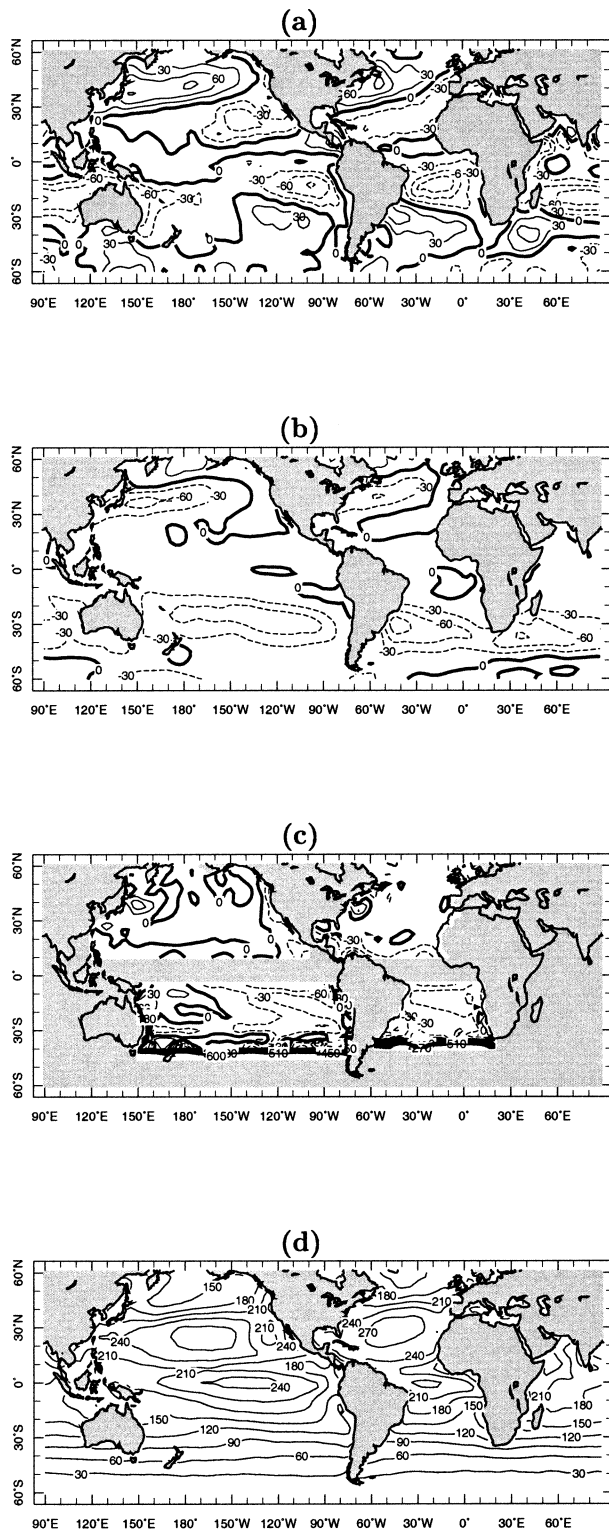


FIG. 5. As in Fig. 4 but for Jun–Jul–Aug.

of ocean processes playing a more important role in the Southern Hemisphere than the Northern Hemisphere. In both the South Pacific and the South Atlantic cooling by ocean processes (Figs. 8e and 9e) in the east is stronger than in the north and drives the strengthening of the SST asymmetry from March to October. Vertical entrainment of cool water is the dominant term, but the cool water is spread west by horizontal advection. Ocean dynamics are more important in explaining the SST asymmetry in the Southern Hemisphere than in the Northern Hemisphere for two reasons. First the winds blow parallel to the shore creating an ideal situation for coastal upwelling year-round that is not matched in the North Pacific south of California (Philander et al. 1996). Second, the waters below the mixed layer are much cooler in the South Pacific and South Atlantic than in the North Pacific or North Atlantic (not shown), which, in turn, may in part be due to raising of the thermocline by the strong alongshore flow but is also influenced by the proximity of the cold waters of the Southern Ocean.

In the South Pacific the mean advection of moist static energy (Fig. 8b) strengthens the SST asymmetry most during local summer, as in the Northern Hemisphere. In the South Atlantic (Fig. 9b) it tends to cool the central ocean relative to the areas to both the east and the west and with little variation through the year. This confirms ocean dynamics to be dominant in creating the observed SST asymmetry and its seasonal cycle in the Southern Hemisphere.

The impact of the transient eddy fluxes in both basins (Figs. 8c and 9c) is weak because the Southern Hemisphere storm track is far more zonally symmetric than its northern counterpart (which splits into two distinct centers east of the Asian and American coasts). Similar to the Northern Hemisphere subtropics, cloud–radiative feedbacks (Figs. 8d and 9d) provide an additional cooling of the SST in the east *after* the strong SST asymmetry has already been established. As in the Northern Hemisphere, the sum of radiative cooling of the boundary layer and the turbulent flux of moist static energy at its top (Figs. 8f and 9f) damps the SST asymmetry.

4. Simulation of subtropical air–sea interaction with atmospheric GCMs coupled to mixed layer oceans

The previous analyses indicated that, while advection by the mean and transient atmospheric circulation is crucial to the generation of the zonal asymmetries of SST, ocean heat flux convergence is also important. In the Northern Hemisphere ocean heat transport maintains the asymmetry during winter and in the Southern Hemisphere cooling by ocean heat flux divergence in the east is the dominant process creating the SST asymmetry.

Next we turn to a comparison of the subtropical anticyclones and asymmetry of SSTs as simulated by two pairs of atmospheric GCMs coupled to mixed layer oceans. In each pair one experiment accounts for the

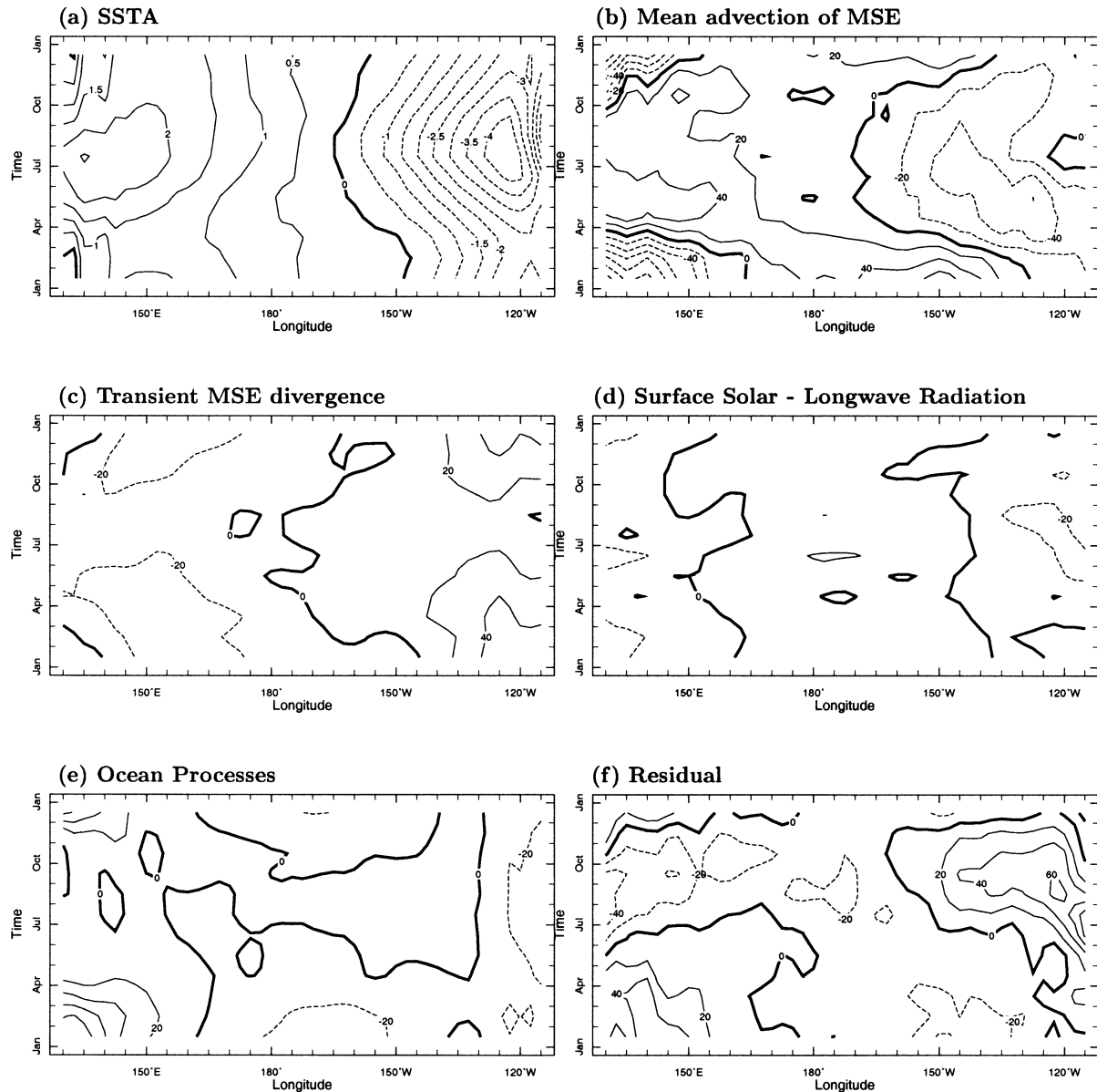


FIG. 6. Time-longitude plots of the (a) SST, (b) mean moist static energy advection, (c) transient eddy flux divergence of moist static energy, (d) net surface radiation, (e) sum of ocean advection and mixing, and (f) sum of boundary layer radiative cooling and turbulent flux of moist static energy at 700 mb for the North Pacific. Data are averaged from 15° – 35° N and are plotted as the departure from the zonal average across the basin. Positive values indicate a warming. Data are from NCEP–NCAR reanalyses except the surface solar radiation, which is from ISCCP and the ocean advection and mixing, which are from the ocean GCM. Units are $^{\circ}\text{C}$ for (a) and W m^{-2} otherwise.

ocean heat transport in the mixed layer and the other experiment does not. On the basis of the observational analysis we expect that the SST asymmetry will be weaker than observed in the runs that do not account for ocean heat transport. However, the observational analysis cannot tell us what forces the seasonal cycle of the subtropical anticyclones. Here we examine whether weakening the zonal asymmetry of SSTs when the ocean heat transport is removed impacts the strength and seasonal cycle of the anticyclones.

The sea level pressure and deviation of SST from

zonal symmetry for the two GISS models, for December–February and June–August, are shown in Fig. 10 and the same results from the CCM3 model are shown in Fig. 11. The models with the q -flux produce reasonable simulations of the seasonal cycle, strength, and location of the subtropical anticyclones as can be seen by comparing Figs. 10a,c and Figs. 11a,c with Figs. 1a,c.

Looking at the asymmetry of SST, it is clear that the basic patterns of warmer and colder SST than the zonal mean are reproduced in both models (and in midlatitudes

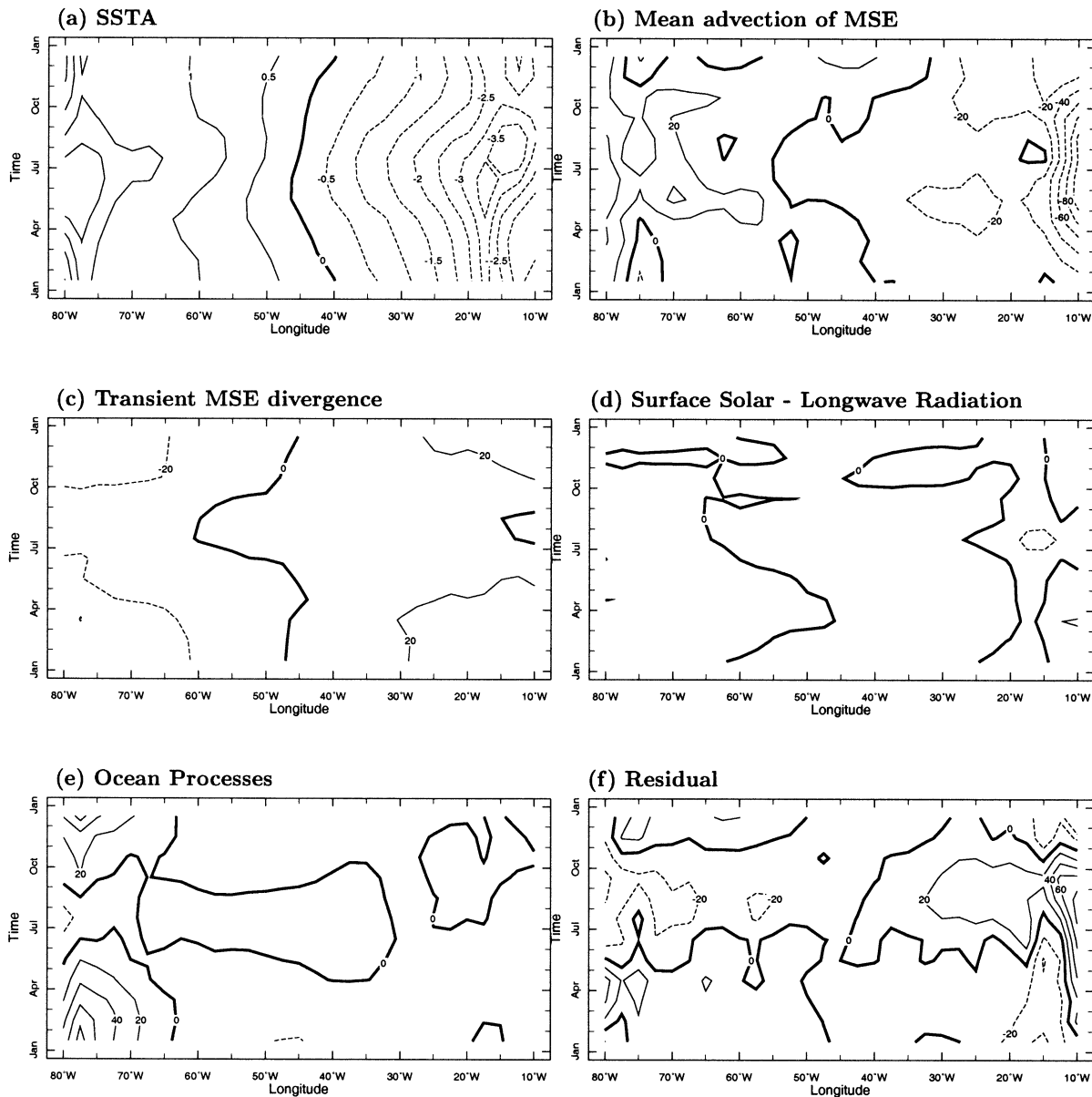


FIG. 7. As in Fig. 6 but for the North Atlantic (15° – 35° N).

as well as in the Tropics) but the asymmetry across the subtropical oceans is much weaker when the ocean heat transport is removed. When the ocean heat transport is removed the maximum SST asymmetry in the Northern Hemisphere still occurs in local summer but now it also occurs in local summer in the Southern Hemisphere. This supports the suggestion that ocean dynamics are the reason why the observed SST asymmetry in the Southern Hemisphere maximizes during local spring. During Northern Hemisphere summer the area of the Indo-Pacific warm pool remains the warmest at its latitude, even when ocean heat transport is removed.

The Northern Hemisphere subtropical anticyclones

are not appreciably weaker when the ocean heat transport is removed. In contrast, the Southern Hemisphere anticyclones weaken when the ocean heat transport is not accounted for. In both hemispheres the anticyclones are best defined in local summer whether or not the ocean heat transport is accounted for. Also, in both hemispheres during local summer, high pressure extends unrealistically far eastward in the western basins when the ocean heat transport is removed. The ocean heat transport, by causing warming in the west, therefore helps locate the summer anticyclones over the eastern parts of the oceans.

The GCMs have much less low-level cloud cover over

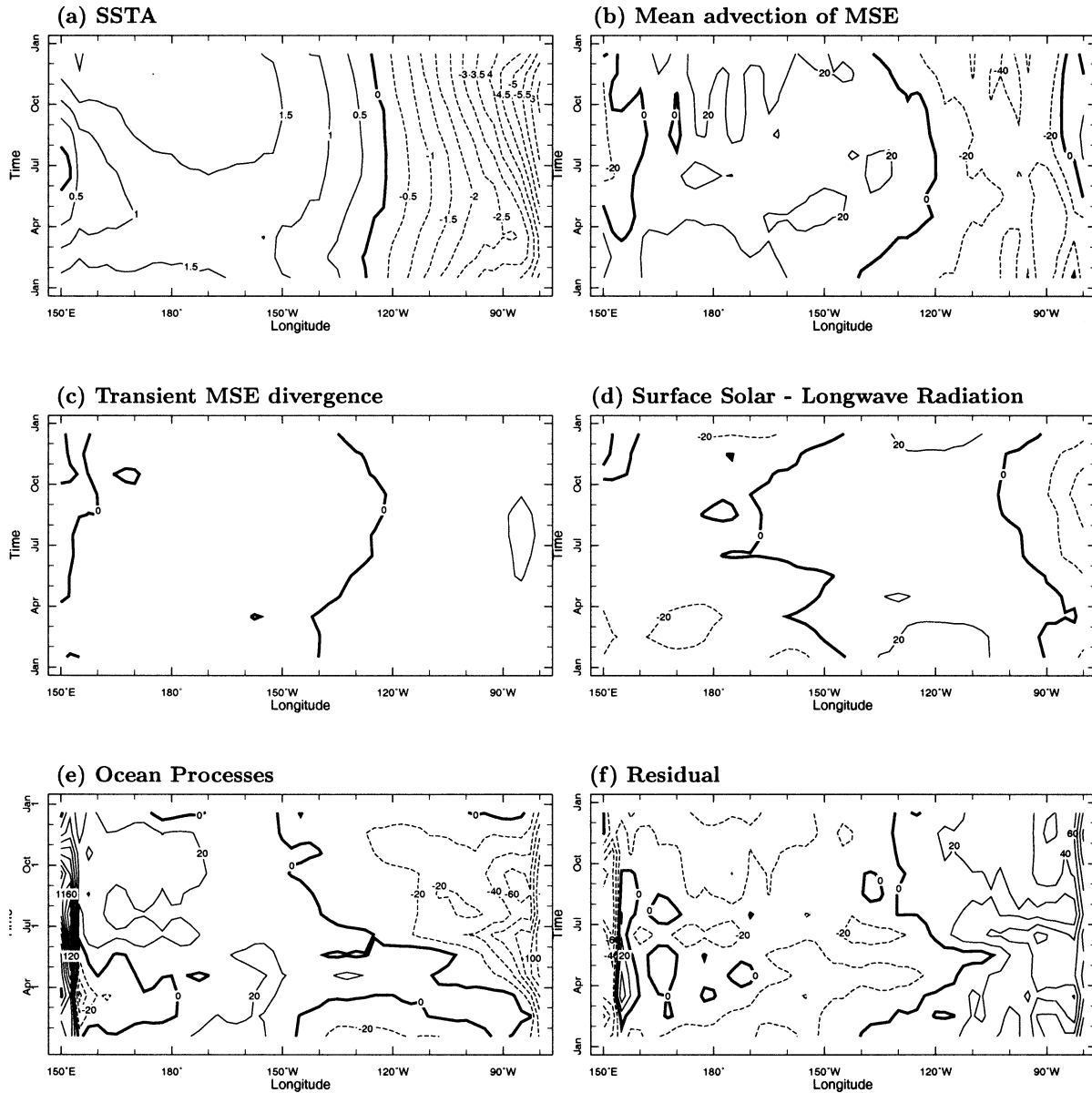


FIG. 8. As in Fig. 6 but for the South Pacific (5° – 25° S).

the eastern subtropical oceans than is observed and consequently underrepresent their cooling effect. This model deficiency helps explain why the SSTs are too warm in the far eastern subtropical basins, but it is also clear that the clouds have little direct or indirect impact on the atmospheric circulation within these models.

The GCM results support the idea that ocean dynamics are required to achieve the strength of the observed subtropical SST asymmetry. Yet they also indicate that in the Northern Hemisphere the full asymmetry of the SST is not required for the subtropical anticyclones to achieve full strength while in the Southern Hemisphere it is. Since the precipitation over the tropical and subtropical oceans

is closely related to SST, there are two possible explanations for these results. First, in the Northern Hemisphere, the subtropical anticyclones are forced largely by orography and heating over land and these forcings are hardly altered when ocean heat transport is removed. Alternatively the subtropical anticyclones are forced by heating over both ocean and land, but the weak SST asymmetry and warm Indian and west Pacific Oceans, still present when ocean heat transport is removed, is enough to place the ocean precipitation in the correct location. In the Southern Hemisphere ocean heat transport is required to get both the SST asymmetry and the full strength of the subtropical anticyclones.

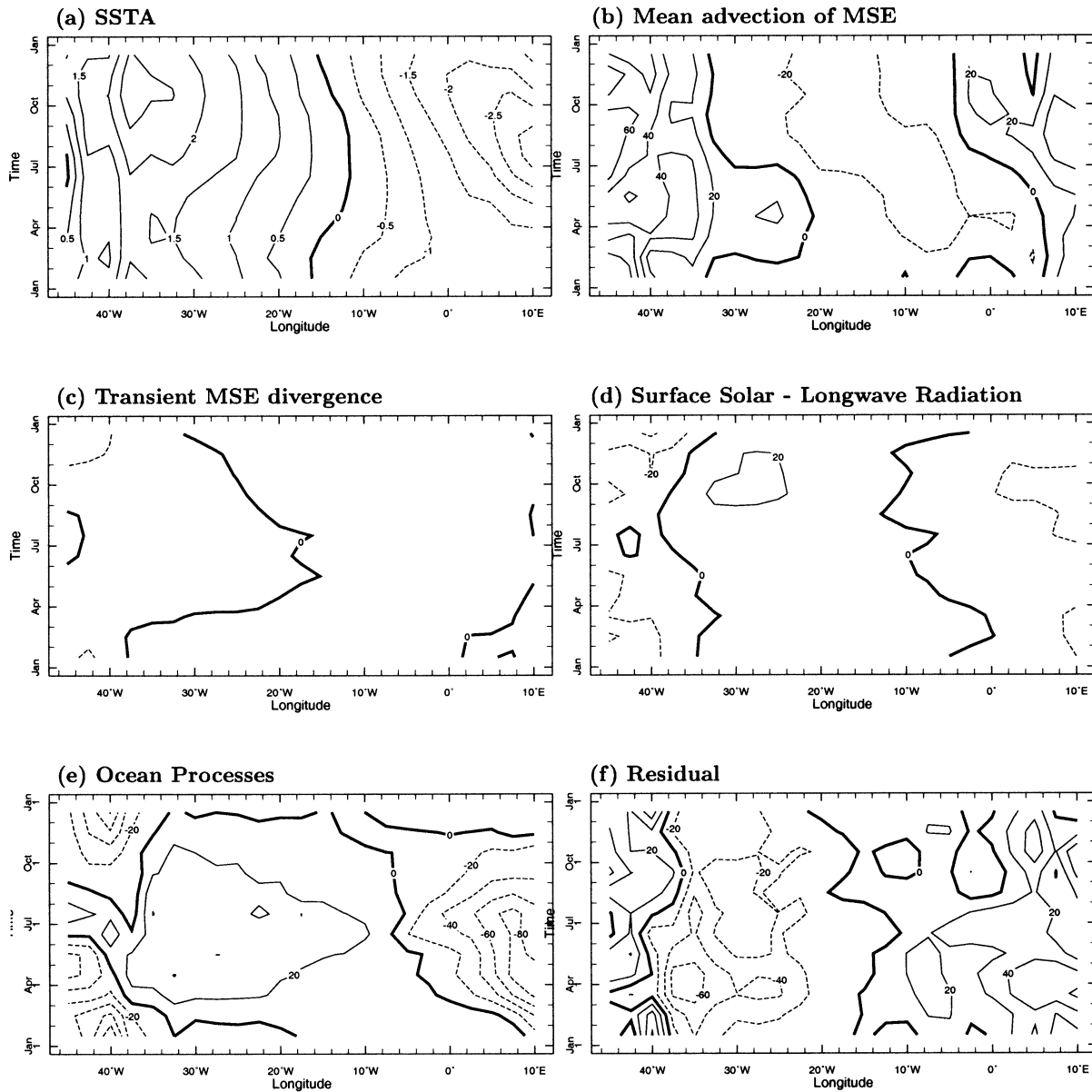


FIG. 9. As in Fig. 6 but for the South Atlantic (5° – 25° S).

5. An idealized atmosphere–ocean model of subtropical air–sea interaction with imposed heating

The experiments with the atmospheric GCMs coupled to the ocean mixed layer have made it clear that the subtropical anticyclones retain much of their character when ocean heat transport is removed. However local air–sea interactions may still influence the pattern of atmospheric heating that provides the forcing for the anticyclones. In this section we will address the relative importance of the heating over the land and the sea. As in RH we assume that the monsoon is “triggered by land–sea sensible heating contrasts and is taken as giv-

en.” Here we use an idealized model to examine the circulation and associated zonal asymmetry of SSTs, forced first by monsoon heating over land alone and then by heating over land and ocean. Then, by removing the ocean precipitation in the off-equatorial monsoon regions, we will demonstrate how the atmospheric circulation forced by heating over land creates asymmetries of SST that favor convection over the western oceans, which reinforces the original circulation.

The simple model of air–sea interaction contains an ocean mixed layer in which the SST is determined by surface fluxes of sensible heat and moisture alone, and an atmosphere model forced by imposed heating.

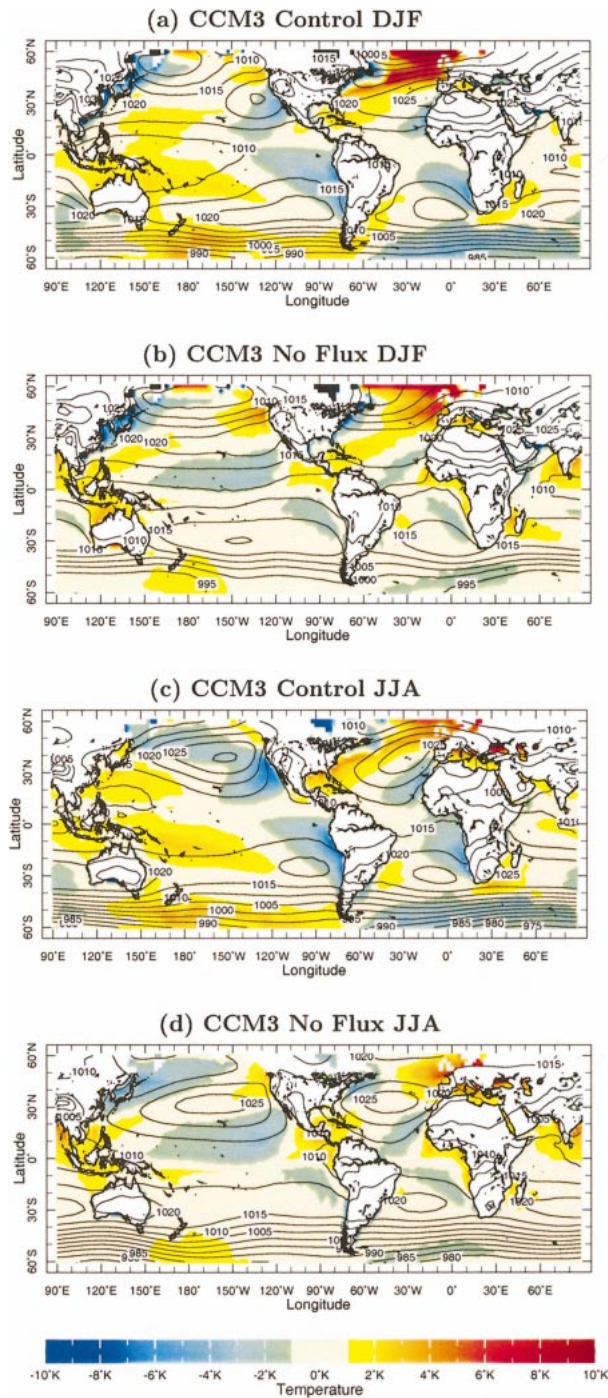


FIG. 11. As in Fig. 10 but from the CCM3 atmospheric GCM coupled to a mixed layer ocean.

the temperature and humidity distribution over the ocean and, therefore, the SST.

b. Ocean mixed layer model

The seasonally varying zonal mean SST, $\langle T_s \rangle$, is specified from observations (NCEP–NCAR reanaly-

sis). The SST departure from zonal mean, T_s^* , is determined from

$$\frac{\partial T_s^*}{\partial t} = -\frac{\rho_a c_E}{\rho_w c_p H} [U(c_p \Delta T + L\Delta q) - \langle U(c_p \Delta T + L\Delta q) \rangle], \quad (7)$$

where U is the wind speed and H is the model ocean mixed layer depth (50 m); ΔT and Δq are the air–sea temperature and humidity differences given by

$$\Delta T = T_s^* + \langle T_s \rangle - T, \quad (8)$$

$$\Delta q = q_s^* + \langle q_s \rangle - q, \quad (9)$$

where q_s^* and $\langle q_s \rangle$ are the zonally asymmetric and zonally symmetric surface saturation humidity and T and q are the lowest-level air temperature and specific humidity from the atmosphere model. Consequently, T_s^* is determined by the departure from the zonal mean of the surface latent plus sensible heat flux. We ignore the impact on the SST asymmetry of zonal asymmetries in the net surface radiation. As shown in section 3c, these are of lesser importance relative to the three-dimensional advection of moist static energy, but their neglect will cause an underestimation of the modelled SST asymmetry. Asymmetries of SST are driven by atmospheric motions that alter the air temperature and air humidity, modifying the surface fluxes and altering the SST until the departure from zonal mean of the latent plus sensible surface flux returns to zero, satisfying Eq. (7).

c. Model results

The model is integrated for 10 yr, by which time the gross features are well established and steady. In Fig. 12 we show the sea level pressure and SST asymmetry during DJF forced by imposed heating over all land only (Fig. 12a, contour interval of 2 mb), by imposed heating over all land plus the equatorial oceans between 15°S and 15°N (Fig. 12b, contour interval of 2 mb); and by imposed heating over all land plus all ocean (Fig. 12c, contour interval of 5 mb). The June–August simulations are shown in Fig. 13. In the case with forcing over land only, during winter (Fig. 12a) the flow is quite zonal and in summer (Fig. 13a) the subtropical anticyclones are clearly present but weak (note the small contour interval). The asymmetries of the summer flow are enough to create cold water within the eastern basins and warmer water within the western basins. The opposite sign asymmetry in the mid- and high-latitude North Atlantic is not recreated because of the lack of a developed Icelandic low. When the essentially zonally symmetric (ITCZ) forcing in the equatorial region is added (Figs. 12b and 13b) the equatorial trough deepens but the flow becomes more zonal and the Northern Hemisphere subtropical anticyclones and SST asymmetry weaken.

The simulation of the sea level pressure and the SST asymmetry is quite realistic when all the forcing over both land and sea is included (Figs. 12c and 13c). In this case the North Pacific summer subtropical anticyclones achieve full strength but the Atlantic counterpart is displaced. The quadrupole pattern of the SST asymmetry, with opposite sign east–west asymmetric at subtropical and mid to high latitudes, is well recreated.⁴ By comparing to the case that includes forcing over the ocean in only the equatorial region (Figs. 11b and 12b), it is clear that the extensive condensational heating that occurs over the western subtropical oceans greatly strengthens the subtropical anticyclones.

In the Southern Hemisphere neither the identity of the anticyclones nor the SST asymmetry are well reproduced. The ocean GCM demonstrated the importance of ocean heat transport, so the poor simulation of the SST asymmetry is expected. However the simulation of the anticyclones is worse than in the atmospheric GCMs that also ignored the ocean heat transport, indicating that the pattern of diabatic heating in the idealized model, imposed plus computed, is likely wrong. It is noteworthy that RH were also unable to model the southern anticyclones unless they forced their model with the diabatic cooling (deduced from reanalyses) within the column immediately above.

6. A theory for the seasonal cycle of the subtropical anticyclones and associated zonal asymmetries of SST

Based on the analysis of observations and modeling so far reported, the following schematic can be presented for the seasonal cycle in the subtropics. During winter the subtropical latitudes in each hemisphere are occupied by a zonal band of high pressure underlying the subsiding branch of the Hadley cell. During northern winter the subtropical ocean is cooled in the west by outflow of cold, dry air from the Asian and American continents. This cooling is opposed by poleward warm water advection within the western boundary currents ensuring maintenance of the SST asymmetry throughout the winter. As the transition to early summer occurs, convection over subtropical land areas begins and breaks the zonal symmetry of the atmospheric circulation. Vorticity balance requires poleward low-level flow into the regions of deep convection, while the part of the heating that is symmetric about the equator continues to force equatorial low pressure to the east via a Kelvin wave. Over the eastern oceans, where there is no deep convection, vorticity balance requires that radiatively driven descent be balanced by equatorward low-level flow. In combination with weak midlatitude

westerlies this completes the formation of weak closed subtropical anticyclones. Air–sea interaction then comes into play to strengthen the anticyclones.

Descent in the east causes subsidence drying and cools the SST while, in the west, poleward flow warms by horizontal advection. As a result, as the transition to summer occurs, the SST warms more in the west than in the east. The atmosphere becomes very stable to deep convection in the east and unstable in the west, allowing monsoonal convection over land to spread to adjacent ocean regions. This is assisted by warming of the western oceans by ocean heat transport. The extensive convection over the western subtropical oceans, and over the Indian Ocean, greatly enhances the forcing of the subtropical anticyclones and positions them over the eastern basins. The SST asymmetry is then strengthened by the enhanced atmospheric circulation, and is further enhanced by increased low cloud cover within the stable boundary layer in the east and by coastal upwelling. The vertical convective flux of moist static energy damps the SST asymmetry. Ultimately the subtropical anticyclones and the SST asymmetry weaken as summer ends and the precipitation, first over the subtropical land areas and later over the subtropical oceans, weakens and finally shifts to the other hemisphere.

Ocean dynamical cooling of the eastern oceans is very important in the Southern Hemisphere but is auxiliary in the north. During Southern Hemisphere winter, when the subtropical anticyclones are weak, strong southeasterly flow occurs along the coasts of South American and southern Africa as part of the winter Hadley cell, causing strong upwelling and westward advection in the ocean and cooling. Ocean heat transport is important in explaining the Southern Hemisphere SST asymmetry and causes a noticeable strengthening of the southern subtropical anticyclones.

7. Conclusions

We have attempted to explain the seasonal cycle of the atmospheric circulation and the surface temperature of the ocean in the subtropics and assess the degree to which they arise as a coupled phenomena. The conclusion are as follows:

- In agreement with Rodwell and Hoskins (2001) the subtropical anticyclones owe their existence to monsoonal heating during summer over land. However the anticyclones thus forced are weak.
- Enhancement of the subtropical anticyclones requires air–sea interaction. Once the subtropical anticyclones have been forced by heating over land, subsidence of dry air over the eastern subtropical oceans lowers the SST while poleward lower tropospheric advection over the western subtropical oceans raises the SST. The atmosphere is stabilized to deep convection in the east but becomes unstable in the west. It is suggested that this allows the spread of deep convection from

⁴ The mid- to high-latitude asymmetry arises as the winter Aleutian and Icelandic lows achieve full development in response to orographic forcing and diabatic heating over the midlatitude oceans [see Seager et al. (2002)].

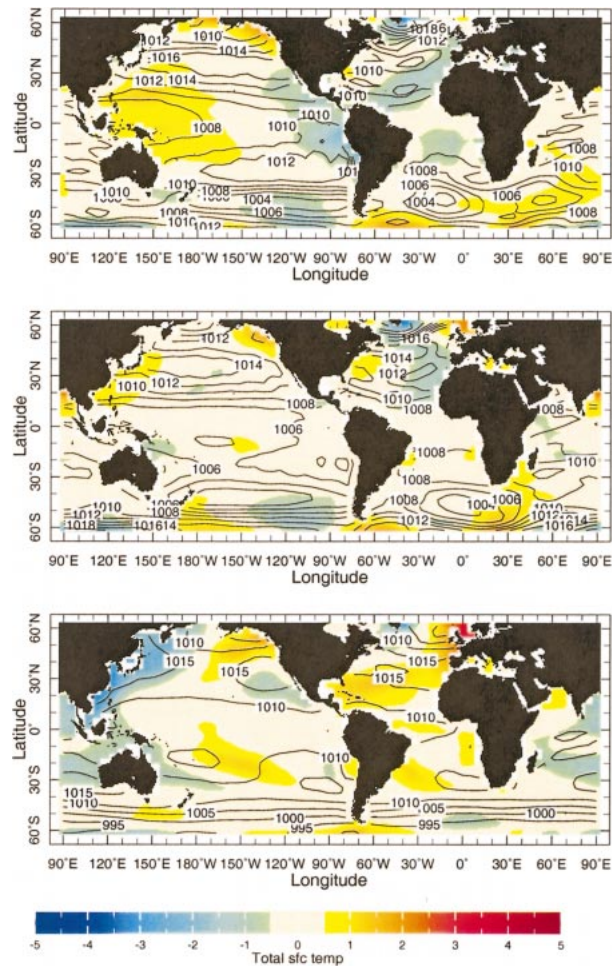


FIG. 12. (a) The sea level pressure (mb) and SST asymmetry ($^{\circ}\text{C}$) in the idealized model forced by observed condensational heating over (a) land (contour interval of 2 mb), (b) land plus the equatorial ocean (contour interval of 2 mb), and (c) all land and all ocean (contour interval of 5 mb) for Dec–Feb.

land areas to nearby areas of the subtropical oceans, amplifying the forcing of the atmosphere circulation and bringing the subtropical anticyclones up to full strength. Further experiments are needed to prove that the distribution of atmospheric convection is influenced in this way. If it is, then this is a positive feedback.

- The positive feedback is held in check by the convective cooling of the SST. More fundamentally the seasonal cycle prevents further growth as winter approaches and the western oceans are cooled by outflow of cold, dry air from the continents, and both land and ocean convection retreat equatorward.
- In the Northern Hemisphere the SST asymmetry is fundamentally forced by the atmospheric circulation but its full strength requires poleward advection of warm water in the western boundary currents. However the atmospheric circulation alone is enough to

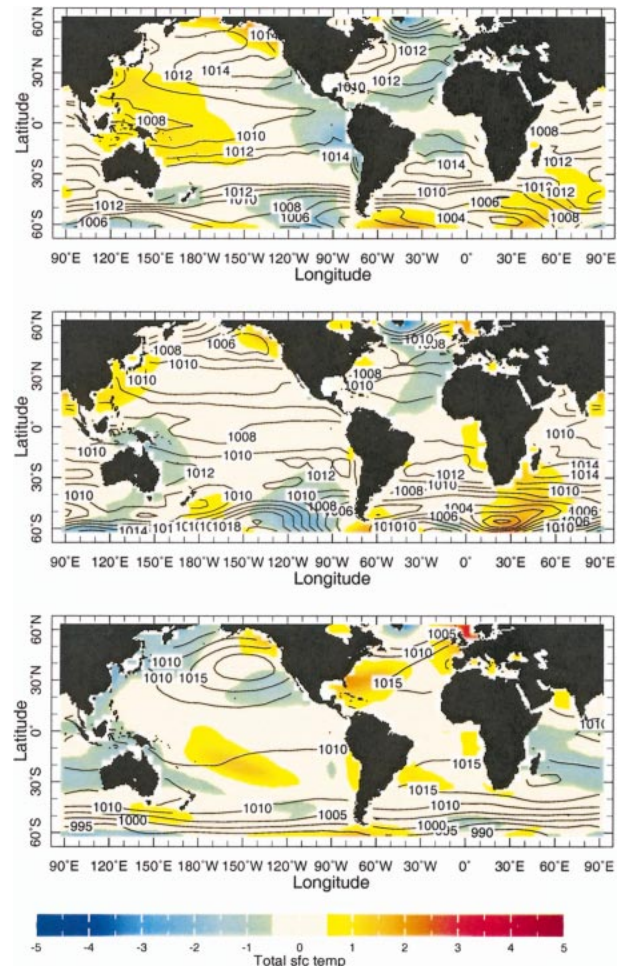


FIG. 13. As in Fig. 12 except for Jun–Aug.

create sufficient SST asymmetry that the deep convection over the ocean is placed in the west.

- Cloud–radiation interactions further cool the eastern subtropical oceans after other processes have already made them cool, but have little subsequent impact on the atmospheric circulation.
- In the Southern Hemisphere ocean upwelling and advection drives the seasonal cycle of the SST asymmetry and causes a strengthening of the southern anticyclones while not greatly influencing their seasonal cycle. However, in the idealized model presented here, and in Rodwell and Hoskins (2001), these were not the most difficult of the anticyclones to model, indicating that we too have not fully explained their origin.

These conclusions build on the earlier work of Rodwell and Hoskins (2001), Chen et al. (2001), and Ting (1994) by addressing the role of air–sea interaction in maintaining the summer stationary waves. We have shown how the atmospheric circulation forced by monsoonal convection over land creates zonal asymmetries of SST that favor convection over the western ocean

basins, providing a diabatic forcing for the atmosphere that enhances the subtropical anticyclones. The ocean, through a combination of mixed layer processes and heat transport, plays a crucial role in the seasonal cycle of the subtropical anticyclones and in positioning them in the eastern basins. In the Southern Hemisphere in particular, ocean heat transport is critical in generating the observed strength of the SST asymmetry and causes a noticeable strengthening of the atmospheric circulation.

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APPENDIX

Ocean Mixed Layer Heat Budget

The temperature of the mixed layer of the ocean model is determined by horizontal and vertical advection within the mixed layer and across the mixed layer base, by the net surface heat flux less the deep penetration of solar radiation below the mixed layer, and by vertical mixing. The temperature equation is given by

$$\rho c_p \left(\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right) = \frac{\partial Q}{\partial z} - \rho c_p \frac{\partial (\overline{w'T'})}{\partial z}. \quad (\text{A1})$$

Here most terms have their usual meaning $\partial Q/\partial z$ is the vertical convergence of the net radiative and turbulent surface fluxes and equals the net surface heat flux (defined positive downward) minus solar radiation transmitted out of the bottom of the mixed layer, and $\partial \overline{w'T'}/\partial z$ is the turbulent mixing.

Integration from the bottom of the mixed layer $z = -H$ to the surface we get

$$\begin{aligned} \rho c_p H \frac{\partial T}{\partial t} = & -\rho c_p \left[H \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) \right. \\ & \left. - (T - T_H) \left(u \frac{\partial H}{\partial x} + v \frac{\partial H}{\partial y} \right) \right] \\ & - \rho c_p \left[(T - T_H) \left(\frac{\partial H}{\partial t} + w_H \right) + \overline{(w'T')}_H \right] \\ & + Q_{\text{sfc}}^{\text{net}} - Q_H^p, \end{aligned} \quad (\text{A2})$$

where T_H is the temperature immediately below the mixed layer, w_H is the vertical velocity at the base of the mixed layer, $Q_{\text{sfc}}^{\text{net}}$ is the net surface heat flux, and Q_H^p is the transmitted solar radiation. The first bracketed term is the SST tendency due to horizontal processes and the second bracketed term is the tendency due to vertical processes. The sum of these we call the SST

tendency due to ocean processes. In the Murtugudde et al. (1996) model used in the Southern Hemisphere the vertical integral is just over the bulk mixed layer, while in the Lamont-Doherty ocean GCM we explicitly integrate the advective terms over the levels within the mixed layer and these terms in Eq. (A2) should be thought of in that way.

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