The Climate Response To Basin-Specific Changes In Latitudinal Temperature Gradients And The Implications For Sea Ice Variability

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ABSTRACT

Recent trends in sea ice have raised the question of how much is associated with greenhouse warming, and how much is the result of oscillations within the climate system. To address this issue, we investigate the effect of changes in latitudinal temperature gradients on circulation and sea ice at high latitudes in a set of experiments with the GISS GCM. Sea surface temperature gradients are increased/decreased in all ocean basins, and are also changed in the different directions in different ocean basins, without allowing sea ice to change. Additional experiments allow sea ice growth/reduction with the altered temperatures. The results show that while increased gradients deepen the subpolar lows in both hemispheres, during winter they have little effect on sea level pressure over the Arctic, unless sea ice is allowed to change. With Arctic sea ice reductions, the sea ice response acts as a positive feedback, inducing cyclonic circulation changes that would enhance its removal, as may be occurring due to the current high phase of the North Atlantic Oscillation. In the Southern Hemisphere, gradient changes in one ocean basin reduce storm intensities in that basin, by shifting storm tracks equatorward and away from the potential energy source associated with cold air advection from Antarctica. Alterations of the gradient in one ocean basin change longitudinal temperature gradients; an increased gradient in one basin from tropical heating results in subsidence in the tropics in the other basin, mimicking the effect of a decreased gradient in that basin. Hence in many respects, regional effects, such as the strength of subpolar lows in the Northern Hemisphere are amplified when the gradient changes are of opposite sign in the two ocean basins, and in the Southern Hemisphere, a gradient increase in one ocean basin strengths storms (by moving them

poleward) in the other basin. This latter effect may explain observed sea ice variations (the Antarctic dipole) which are out of phase in the two ocean basins in the Southern Hemisphere, as well as upper ocean variability in the Weddell gyre.

I. INTRODUCTION

The recent changes in Northern Hemisphere sea ice coverage and thickness (Parkinson et al., 1999; Rothrock et al., 1999; Johannessen et al., 1999) have raised the issue of whether they are indeed trends or part of natural variability patterns. One of the most robust projections of GCMs in response to increasing anthropogenic trace gases is a decrease in Northern Hemisphere sea ice. Is what we are currently seeing, the decrease of 2.8 %/decade over the 40 years, and the noticeable thinning of ice throughout the region, the expected beginning of this process? If so it has strong implications for high latitude warming and a positive sea ice/albedo feedback.

Alternatively, the sea ice changes could be the response to the increasing frequency of the high phase of the Arctic Oscillation (AO) (or the closely-related North Atlantic Oscillation) (Hurrell, 1995; Walsh et al., 1996; Thompson and Wallace, 1998) characterized by lower pressure over the pole. The cyclonic circulation associated with this change could be leading to greater export of ice through the Fram Strait (Mysak et al., 1996; Kwok and Rothrock, 1999; Polyakov et al., 1999; Kwok, 2000; Hilmer and Jung, 2000, Desser et al., 2000), reducing Arctic ice cover. This circulation can also alter the surface freshwater distribution leading to a loss of the Arctic cold halocline layer and commensurate initiation of significant ocean heat flux resulting in considerable winter ice thinning (Martinson and Steele, 2000). This would then be a dynamic forcing, rather than the primarily thermodynamic forcing described above.

Even if this were the cause, it would not necessarily indicate whether it was the result of natural or anthropogenic forcing. The increased high phase of the AO might simply represent natural variability in the system, and be reversed at any moment. Or it might represent forcing associated with greenhouse gases. In one mechanism, Shindell et al. (1999) suggested that it arose through the response of the system to increased greenhouse gases, via the impact on the temperature gradient and zonal wind structure. Along a constant pressure surface intersecting the tropopause, greenhouse gas increases induce tropospheric warming at lower latitudes and stratospheric cooling at higher latitudes. This gradient change results in stronger zonal winds in the lower stratosphere, forcing more equatorward planetary wave propagation. Poleward angular momentum transport associated with this change in wave refraction strengthens the zonal winds in the lower stratosphere, and the subsequent effect on planetary waves in the troposphere allows the effect to extend down to the surface. In this scenario, and in the model, the effect is likely to continue. observations suggest this mechanism may indeed be operating (Baldwin and Dunkerton, 1999; Thompson and Wallace, 2000).

Another possible relationship to global warming emphasizes the similarly increased high phase of the North Atlantic Oscillation, but ascribes it to changes in North Atlantic heat transports (Fyfe et al., 1999; Russell et al., 2000). Anthropogenic greenhouse-initiated warming of the tropical oceans, associated with the shallow tropical mixed layer depths, produces more moisture in the atmosphere. This added moisture is subsequently advected poleward, and in the North Atlantic results in increased rainfall, which freshens the ocean. North Atlantic Deep Water (NADW) production and associated oceanic poleward heat transport is inhibited, cooling the North Atlantic. The increased temperature gradient in the Atlantic is then associated with stronger west winds. Observations of an apparent shift in NADW production from the Norwegian to the Labrador Sea might be part of this pattern, and cooler surface air temperatures have been observed over the

North Atlantic region (e.g., Hansen et al., 1999). Vinnikov et al., (1999) concluded that the decrease in Arctic sea ice is most likely a consequence of greenhouse warming, with a small chance that it could occur from natural variability, based on the results of simulations with the Geophysical Fluid Dynamics Laboratory coupled atmosphere-ocean model.

While one mechanism favors forcing from above the troposphere, and the other forcing from below, what they have in common is a change in the latitudinal temperature gradient associated with tropical warming and extratropical cooling. This raises the more general question of the response of circulation features at high latitudes to altered latitudinal temperature gradients, both globally and in various ocean basins. If the North Atlantic cools due to NADW suppression, global warming could lead to a locally increased temperature gradient in that basin. If NADW production does not change, then the expected high latitude amplification of climate forcing should result in a decreased latitudinal temperature gradient.

In the North Pacific, standard GCM scenarios show a reduction in temperature gradient, again due to high latitude amplification processes such as sea ice reduction. However, if El Nino frequencies were to increase, or become permanent as in some GCM scenarios, then the Pacific temperature gradient might well increase. The high latitude circulation systems would presumably respond uniquely in these different cases, with various combinations possible, as would be the effect on sea ice advection and sea ice change. Furthermore, the result would be interactive: the more sea ice reduction, the more of an increase in latitudinal temperature gradient likely.

What about in the Southern Hemisphere? In a recently submitted paper, Yuan and Martinson (2000) have shown that variations occurring in sea ice coverage are out of phase between the eastern Pacific and Atlantic.

They, as well as others, suggest that this response is related to ENSO (Carleton, 1987; Simmonds and Jacka, 1995; Ledley and Huang, 1997). Moreover, Yuan et al. (1999), in a case study of storm activities in late 1996 based on space-based observations of surface winds, found that there was more cyclonic activity in the South Pacific and less in the South Atlantic. Could it be the result of a latitudinal temperature gradient change in the South Pacific due to the La Nina conditions that existed in 1996? Likewise, Martinson and Iannuzzi (2000) find that the upper ocean characteristics of the Weddell gyre co-vary with the sea ice and ENSO in a manner they hypothesize reflects enhanced winter cyclonic forcing during El Nino periods and diminished cyclonic forcing during La Nina. Can we understand why this would cause an alternation in sea ice and polar sea ice changes in the different ocean basins?

The experiments described below are used to examine these questions in the context of a general circulation model (GCM). We shall show that altered latitudinal gradients will affect pressures at high latitudes, in ways that are unique to the different ocean basins, and differ from the Northern to Southern Hemisphere.

II. EXPERIMENTS

Our intent is to provide a general discussion of the types of processes that arise when gradients are changed, either uniformly or in one ocean basin relative to another. In that sense, we are not attempting to simulate any particular climate, past or future, though some features of our experiments may be similar to characteristics found in some paleoclimate and future climate scenarios, as well as in ENSO-related variability. The gradient changes we use are therefore generic. Some of the experiments were described in Rind (1998) (henceforth PAPER 1). Using the GISS 4°x5° Model II' GCM (Rind and Lerner, 1996; PAPER 1; Hansen et al., 1997, where it is referred to as SI 95), the sea surface temperature gradients were changed by increasing (decreasing) tropical temperatures by 3°C, and decreasing (increasing) high latitude temperatures by 6°C, with a linear change in-between. This SST gradient change was chosen to be sufficiently large to produce a clear signal. To put it in perspective, it is associated with a surface air temperature gradient change between the equator and 60°N of ±3.3°C, similar to that associated with 2xCO_2 experiments, about 1/2 that estimated to occur in the Last Glacial Maximum (in the Atlantic) and about double that in typical El Ninos (in the Pacific). The procedure was chosen so as to limit the overall global mean surface air temperature change, which would otherwise provide effects in addition to that associated with the altered gradients. To separate the effects of sea ice changes on the gradient, in most of the experiments sea ice coverage is kept fixed at current day values, so the practical effects of the SST changes do not extend beyond about 70° latitude . In several additional experiments we explore the effects of allowing sea ice to change as well, in which case temperature responses to high latitude warming extend to the north pole.

The following experiments were performed (Table 1). Using the same magnitude gradient changes as described above for PAPER 1, in **Experiment #1**, the SST latitudinal gradient was increased uniformly, while in **Experiment #2** it was decreased. In **Experiment "Ai"** the latitudinal temperature gradient was increased only in the Atlantic Ocean [the Atlantic is defined here as the ocean region from 20°E to as far west as 95°W in the Gulf of Mexico, following the continental outline, with a northern boundary at 72°N]. In **Experiment "Pi"**, the gradient was increased only in the Pacific

Ocean [the Pacific is defined as the ocean region between 65°W and as far east as 120°E near the Philippine Islands]. Similar experiments were also conducted with decreasing the gradients in the individual ocean basins (**Ad**, **Pd**, respectively). In a seventh experiment, the gradient was increased in the Atlantic and decreased in the Pacific (**AdPi**), mimicking results from some increased greenhouse gas experiments. Its inverse was also run (**AiPd**) for comparison. In **Experiment #3** a uniformly increased latitudinal gradient change was combined with a 4°C uniform temperature reduction, and sea ice allowed to increase wherever the SSTs dropped below the freezing point of ocean water (-1.56°C in the model). And in **Experiment #4**, a uniformly decreased latitudinal gradient change was combined with a 4°C uniform increase in temperature, and sea ice was allowed to decrease wherever appropriate. Combining the sea ice changes with a global temperature change amplifies the actual change in sea ice, and allows its effect on high latitude pressure systems to be clearly identified. A complete list of the experiments is provided in Table 1.

In addition to changing the latitudinal gradient, altering sea surface temperatures in individual ocean basins also changes the inter-basin longitudinal gradients. This has the most direct effect in the Antarctic circumpolar region, where the Pacific and Atlantic waters are contiguous. To minimize abrupt longitudinal shifts in that region, we modify the sea surface temperatures between 60° and 70°W to produce smooth gradients. Additional modified transitions occur near the borders of the Indian Ocean with the Atlantic and Pacific.

Each experiment was run for six years, with the results averaged over the final five years. Comparison with 15-year simulations shows that this is sufficient to establish the dynamic differences between simulations with changes as large as these, when sea surface temperatures are specified.

III. RESULTS

a. Sea Level Pressures

Since changes in cyclonicity are the main interest in this context, we show first the variation in sea level pressure, given in Figure 1, for the solstice seasons. To emphasize the effects, we have differenced experiments with opposite gradient changes (henceforth referred to as inverse experiments). As in PAPER 1, the results are consistent with expectations in the Northern Hemisphere: an increased gradient, and larger available potential energy, lead to eddy energy increases. Thus during winter, the Aleutian Low is strengthened when the Pacific gradient is magnified (with a Pacific-North American (PNA) - type teleconnection pattern generated); the Icelandic Low in a southwest position is stronger with the amplified Atlantic gradient. With either ocean basin experiencing an increased gradient, the other ocean basin experiences some pressure rises, reminiscent of the third eigenvector in the 500mb height field normalized covariance matrix (Wallace and Gutzler, 1981). Overall, the North Pacific sea level pressure field seems more responsive to gradient changes than does the North Atlantic when sea ice is invariant, due perhaps to the greater size of the Pacific Ocean and hence the latitudinal gradient change, as well as the greater sea ice in the North Atlantic limiting the effect of the sea surface temperature change. One apparent oddity that will require an explanation is why the differences are larger when gradient changes are of opposite sign in the different ocean basins; for example, the Aleutian Low is deeper in AdPi than it is in Pi. We return to this point below.

Over the Arctic, the increased temperature gradient without any sea ice change (experiment 1 minus 2) produces little sea level pressure response in winter. However, when sea ice is allowed to increase (and decrease in its inverse experiment), sea level pressure is considerably higher (lower) (experiment 3 minus 4). The lower pressure over the pole in experiment 4 will have an additional effect not included here; since increased cyclonic flow leads to a reduction in Arctic sea ice cover, it will have a positive feedback by exposing more open water, decreasing atmospheric stability, and leading to even further increases in cyclonic behavior. During summer, an increased gradient by itself is sufficient to result in higher sea level pressures, perhaps because colder local conditions (and greater vertical stability) dominate the pressure response when horizontal temperature gradients are normally weaker, as in summer.

In the Southern Hemisphere, uniformly increased gradients result in deeper subpolar lows, with and without sea ice changes. During winter the increased low pressure regions are in the South Pacific, while during summer they are primarily in the Atlantic/Indian Ocean sector. This greater cyclonicity even occurs when sea ice is allowed to increase, in contrast to the situation in the Arctic. [As the Arctic is at higher latitudes than the subpolar positions being discussed for the Southern Hemisphere, it has much more sea ice to begin with, and so when sea ice is not allowed to change, it experiences less of a temperature gradient change and less sea level pressure response.]

However, in the Southern Hemisphere, the results for the experiments in which the gradient is changed separately in individual ocean basins provide a very different picture. Now when the gradient increases in one ocean basin, the subpolar low in that basin actually decreases in intensity (higher sea level pressure), while the subpolar low in the other ocean basin strengthens (lower sea level pressure). This is completely opposite to the situation in the Northern Hemisphere. We explain why this occurred below.

b. Storm Tracks and Intensities

To complement the change in standing wave patterns associated with the seasonal average sea level pressure field, we show in Figure 2 the change in the frequency of storms between the inverse experiments with basin-specific changes, and in Figures 3a,b the mean intensity of those storms in Dec-Feb and June-Aug, respectively. The increased Pacific gradient is responsible for a storm track in winter similar to that often associated with El Ninos, from the North Pacific across the southern U.S. and then northeastward into the Atlantic. The Atlantic gradient affects storms primarily in the Atlantic, from the northeastern U.S. eastward across the Atlantic. Note that in the Southern Ocean, with gradient changes in either the Atlantic or Pacific, the storm tracks in both seasons are further equatorward in the ocean basin with the increased gradient, and further poleward in the other basin.

With an increased gradient one would expect stronger storms in the respective ocean basins, and this is clearly true in the North Pacific (Figure 3a). In the North Atlantic the effect is much more muted. In the Southern Ocean, in both seasons, the opposite effect prevails - the storms are weaker in the basin with the increased gradient as the storm track shifts equatorward, and stronger in the other basin (compare, for example, Ai and Ad, or Pi and Pd in Figure 3b).

In general, then, in the Northern Hemisphere gradient change have a somewhat stronger influence on storm tracks and storm intensities in the

Pacific, and the effects of gradient changes on storm intensity in the Southern Hemisphere are opposite to those in the Northern Hemisphere.

c. Jet Stream Changes

An obvious influence on all transient eddy propagation is the change in the jet stream accompanying the gradient differences. Shown in Figure 4a,b are the changes in the 200mb winds for the different inverse experiments in the solstice seasons. With the increased Pacific gradient, the subtropical jet is amplified across the Pacific Ocean, extending downstream over North America, as observed during El Nino events. With the decreased Pacific gradient, the jet stream core shifts poleward. The Atlantic gradient changes affect primarily the subtropical Atlantic winds, especially in winter, with some upstream effect over North America. Similar responses occur in both hemispheres. Note that in the basin-specific gradient change experiments, when the subtropical jet stream increases in one ocean basin, with the core moving equatorward, the jet stream moves poleward in the other basin, again in both hemispheres. The increased cyclonicity apparent with reduced sea ice in experiment 4 is visible in the arctic wind curvature even at this level (the reverse of the result shown in Fig. 4a). Tropical changes also arise, due to the longitudinal circulation effects discussed below.

d. Longitudinal Circulation Effects

To fully understand the results presented above, it is necessary to explore the consequences of another component of these experiments: changing gradients in individual ocean basins gives rise to a change in longitudinal gradients between the ocean basins. These gradient changes then induce longitudinal circulation cells.

Shown in Figures 5-7 are the changes in longitudinal circulation cells and associated parameters for the three different pairs of inverse experiments. When the tropical Pacific is relatively warmer in Pi-Pd (Figure 5), increased rising air and convective heating occurs in the Pacific, and weak subsidence with little heating is induced over the tropical Atlantic (Fig. 5b), a direct consequence of the altered longitudinal sea surface temperature gradients. The longitudinal circulation cell set up results in increased west winds at 200 mb and weak easterlies at the surface, from about 90W to 90E (Fig. 5, top). The temperature and relative humidity increase over the warm Pacific, and relative drying occurs over the Atlantic.

When the tropical Atlantic is warm in Ai-Ad (Figure 6) the situation is reversed, with the warming and rising air now over the Atlantic. Therefore, when the tropical Atlantic is relatively cooler (the inverse of Figure 6), relative subsidence is occurring over the Atlantic, qualitatively similar to what happened with the warmer Pacific. Hence when the tropical Pacific is warmer and the tropical Atlantic cooler, the effects are magnified (and are to some extent additive), as shown by the results in Figure 7 for PiAd-PdAi.

4. DISCUSSION

With the above results we can explain several of the more puzzling features of the sea level pressure field changes. By far the most unexpected result concerns the influence of gradients in one ocean basin on circulation elsewhere. This is particularly true with respect to the low pressure regions surrounding Antarctica. As evident in Figure 1, the sub-polar low pressure systems in that region are actually stronger in the ocean basin that does *not* have the gradient increase. For example, pressures are considerably higher in the Weddell Sea when the Pacific gradient is increased, and lower (i.e., a deeper low) when the Atlantic gradient increases (Fig. 1). As shown in Fig. 4, an increased gradient intensifies the subtropical jet stream in the particular ocean basin, and relocates storms further equatorward. In the Southern Hemisphere this has the effect of moving them further away from Antarctica (Figure 2), and thus further from the potential energy maximum and the strong local latitudinal temperature gradient associated with cold air coming off that continent . The result is a weakening of the storms in the ocean basin with the increased gradient and the more equatorial storm track (Figs. 2,3). The potential feedbacks between the mechanism discussed here and interannual variations of the semi-annual oscillation (van Loon. 1967) is the subject of additional research.

However, why do storms increase in intensity in the other ocean basin? The results from Figs. 5-7 indicate that the increased gradient in one ocean basin results in tropical subsidence in the other basin. This subsidence is qualitatively similar to a decrease in gradient in the other ocean basin, which in the equatorial region similarly results in relative subsidence. The effect is to reduce the meridional circulation rising from the tropics in the ocean basin without the increased gradient, and hence reduce the intensity of its associated subtropical jet stream. As noted with reference to Fig. 3, the jet stream moves poleward over the ocean basin without the gradient increase. Storms thus move poleward, are more exposed to cold air from Antarctica, and hence are more intense (Figs. 2,3).

This alternating basin-effect in storm intensity does not occur in the Northern Hemisphere where storms do not depend on being close to the pole for their cold air source. Cold air advection from higher latitudes follows pathways across the North American and Eurasian continents, which keeps the air relatively unmodified. Eddy available potential energy is maximized when this cold air comes into contact with the warmer air at middle and subpolar latitudes.

Even in the Northern Hemisphere, the intensity of storms (e.g., the Aleutian Low) in an ocean basin is maximized when the gradients are of opposite sign in the two ocean basins. This is the result of the longitudinal circulation cells that arise from changes in gradients in the particular ocean basins. With the Pacific gradient increased and the Atlantic gradient decreased, rising air is somewhat intensified in the tropical Pacific (Fig. 7, middle) (with subsidence in the Atlantic), as is subsidence-induced warming in the subtropical Pacific. This results in a stronger latitudinal temperature gradient and greater eddy kinetic energy at Pacific mid-latitudes.

Given in Table 2 are the eddy energy values in the different experiments during Northern Hemisphere winter. AdPi has both the largest eddy energy and standing wave energy, as well as the largest eddy available potential energy and eddy kinetic energy in the long waves, all features which help explain the greater anomalies in sea level pressure given in Figure 1.

Also shown in Table 2 are the Southern Hemisphere winter values of eddy energy, most of which is in the transient mode (see last column). The uniformly increased gradient experiments (#s 1 and 3) have higher values than the runs with uniformly decreased gradients (#s 2 and 4). The experiments with greater energy in the South Atlantic (Pi and Ad) have larger hemispheric average values than the runs with greater energy in the South Pacific (Ai and Pd). The greatest energy overall is in the combination of experiments which amplify South Atlantic eddy energy, AdPi).

5. RELEVANCE TO OBSERVED SUBPOLAR CHANGES

These results have direct relevance for the currently observed sea ice and subpolar upper ocean variations in both hemispheres. In the Northern Hemisphere, the model indicates that increased SST gradients in the North Atlantic will produce a high-phase "NAO-type" response, with intensification of the Icelandic Low. However, by themselves they do not lead to decreases in sea level pressure over the Arctic (hence no AO signature). To accomplish that requires sea ice decreases, which in these experiments occurs in conjunction with a decrease in latitudinal gradient. Hence the current increase in AO phase would not have been forced directly by the observed increases in the Atlantic temperature gradients (associated for example with reduced NADW production), but could have resulted from sea ice reductions associated with the increased cyclonic flow in conjunction with the Icelandic Low intensification (high phase of the NAO). This latter effect may be the result of natural variations or of greenhouse warming, as discussed in the Introduction. In that sense, the NAO high phase helps generate an AO high phase through its effect on the sea ice field.

In the Southern Hemisphere, the results suggest that alternation in cyclonicity between ocean basins would be expected if a change in latitudinal temperature gradient occurred in one of the basins, as in El Nino or La Nina occurrences. Yuan and Martinson (2000) do in fact see the effects of such alternation between the Pacific and Atlantic in the sea ice field (their so-called Antarctic dipole), as shown in Figure 8. As an example in late austral winter of 1996, the sea ice extent in the Pacific sector of the Antarctic significantly exceeded the normal years (Yuan et al., 1999, Figure 2). The long-lived storms prevailed in the polar/subpolar Pacific regions. On the other hand, the Southern Atlantic experienced much less cyclone activity during the same period. Although Yuan et al. (1999) did not examine the variations of latitudinal temperature gradient in each basin, there is a La Nina event occurring in the tropical Pacific in 1996. We would expect a weaker latitudinal temperature gradient in the South Pacific relative to the El Nino condition. The alternation of the strength of storms between the ocean basins may well be associated with the weaker latitudinal temperature gradient during the La Nina year, as suggested by and consistent with the model results.

The results here are also consistent with the upper ocean response observed by Martinson and Iannuzzi (2000), whereby an El Nino event drives an increased meridional temperature gradient in the Pacific and induces an opposite influence in the Atlantic basin. The latter leads to enhanced cyclonic forcing of the Weddell gyre. This is consistent with their finding of enhanced spin up of the gyre in El Nino years, and the opposite effect for La Nina years.

5. CONCLUSIONS

Increasing the latitudinal temperature gradient in all ocean basins, without allowing sea ice to change, strengthens the subpolar lows in both hemispheres, but has little effect on sea level pressure over the Arctic Basin in winter. However, when sea ice is allowed to decrease, lower pressure occurs over the Northern pole as well. Hence, if increased latitudinal temperature gradients in the Atlantic or Pacific result in increased advection of sea ice out of the Arctic or reduced winter ice growth, the reduced sea ice cover will likely result in lower atmospheric pressure, which would further increase cyclonic wind flow and sea ice advection. Whatever is responsible for the increased phase of the NAO may, therefore, be producing similar effects via this positive feedback between the AO and sea ice reduction.

In the Southern Hemisphere, increasing the latitudinal temperature gradient in only one ocean basin results in decreased storm intensity in that basin. This occurs as a result of the intensified subtropical jet stream, which accompanies the increased gradient, redirects storm tracks equatorward, moving them further from the potential energy source associated with the cold air coming off Antarctica. At the same time, an increased gradient in one ocean basin in the Southern Hemisphere results in increased storm intensity in the other ocean basin. This effect is explained by the fact that an increase in the latitudinal gradient in one ocean changes the longitudinal temperature contrast with the other ocean basin. Consequently, warming of the tropical Pacific results in relative subsidence over the tropical Atlantic, an effect which mimics, to some extent, a decrease in the Atlantic Ocean latitudinal temperature gradient (which also produces subsidence in the tropical Atlantic). So, consistent with recent observations, increasing the temperature gradient in the Pacific weakens the subtropical jet stream in the Atlantic, allowing a poleward shift of the storm tracks, and generating stronger storms in that ocean basin; and vice versa.

In general, then, effects are strongest when a gradient change in one ocean basin is accompanied by a gradient change of opposite sign in the other ocean basin. Variations in sea ice coverage, observed to be out of phase in the two ocean basins in the Southern Hemisphere, might result from this process, and accompany ENSO-induced latitudinal temperature gradient changes.

These results suggest that changes in temperature gradients in the current climate are related to observed sea ice variations in both hemispheres. In the Northern Hemisphere the sea ice change can produce a positive feedback, by amplifying wind changes that are helping to produce the sea ice response. For future climate considerations, the amplifying effect of opposing changes in latitudinal temperature gradients in different ocean basins could magnify sea ice changes, were they to occur as suggested in the

Introduction. This amplification of regional effects is true for other parameters as well, such as rainfall over land areas, a result which will be explored in a subsequent paper.

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FIGURE LEGENDS

Figure 1. Sea level pressure differences between the different experiments. Shown are the changes between experiments 1 and 2 (top), 3 and 4 (second row), Ai and Ad (third row), Pi and Pd (fourth row) and AdPi and Ai Pd (bottom). Results are given for December through February on the left, and June through August on the right. The sea level pressure differences are five year averages.

Figure 2. Change in storm frequency for Pi-Pd (top), Ai-Ad(middle) and AdPi-AiPd (bottom) for December-February (left) and June-August (right). Storms are defined on the sea level pressure maps as closed lows with mean pressures less than 1000 mb.

Figure 3. Average storm intensity (central pressure) for the experiments with ocean-specific gradient changes . (a) December-February; (b) June-August.

Figure 4. 200 mb wind speed changes between the experiments, for (a)December-February, and (b)June-August. The arrows indicate the direction of wind change, the shading indicates the magnitude of the change. For clarity, only one-half of the arrows are shown.

Figure 5. Tropical changes (6N-6S) between Pi and Pd for zonal wind at 950 and 200 mb (top), vertically integrated vertical velocity and moist convective heating (middle), and upper tropospheric temperature and relative humidity (bottom).

Figure 6. As in Figure 5 for Ai minus Ad.

Figure 7. As in Figure 5 for AdPi-AiPd.

Figure 8. The Southern Hemisphere sea ice edge anomaly (containing only the first two modes variability accounting for 53% of the total variance) in the unit of degree of latitude as a function of time and longitude. Note the out of phase relationship between the Atlantic and Pacific Ocean sectors.

Table 1. Description of experiments

Label	Description
#1	Increased gradient in all ocean basins
#2	Decreased gradient in all ocean basins
#3	Increased gradient in all basins plus 4°C cooling and increased sea ice
#4	Decreased gradient in all basins plus 4°C warming and reduced sea ice
Ai	Increased gradient in Atlantic Ocean
Pi	Increased gradient in Pacific Ocean
Ad	Decreased gradient in Atlantic Ocean
Pd	Decreased gradient in Pacific Ocean
AiPd	Increased gradient in Atlantic, decreased gradient in Pacific
AdPi	Decreased gradient in Atlantic, increased gradient in Pacific

Table 2. Northern Hemisphere winter eddy energies in the different experiments. All units 10^{17}J.

	EDDY KINETIC ENERGY	STAND. EDDY KINETIC ENERGY	TRANS. EDDY KINETIC ENERGY	EKE WAVES 1-4	EAPE WAVES 1-4	EKE S.H. JUNE-AUG
CONT	1646	510	1136	803	3460	1779
#1	1882	543	1339	934	3411	1962
#2	1502	510	992	755	3647	1647
#3	1957	461	1496	932	4329	2048
#4	1623	385	1238	850	4555	1548
Pi	2026	808	1218	1122	3665	2130
Pd	1673	552	1121	857	3516	1763
Ai	1690	588	1102	830	3456	1805
Ad	1746	493	1253	900	3619	1964
AdPi	2138	938	1200	1239	3803	2209
AiPd	1757	524	1233	910	3475	1836
STD	35	28	30	23	66	42

Sea Level Pressure (mb)

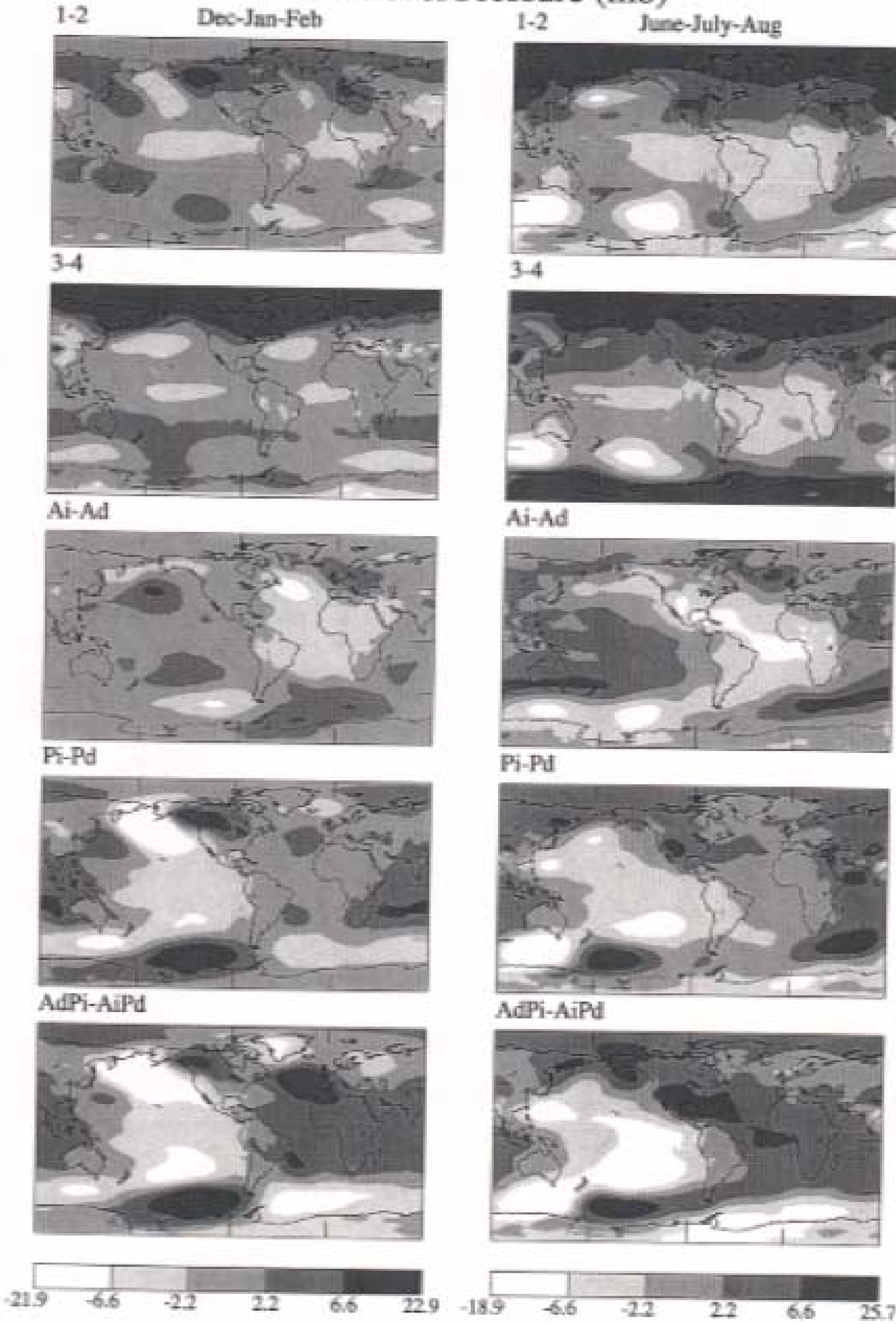


Fig. 1

Frequency of Storms

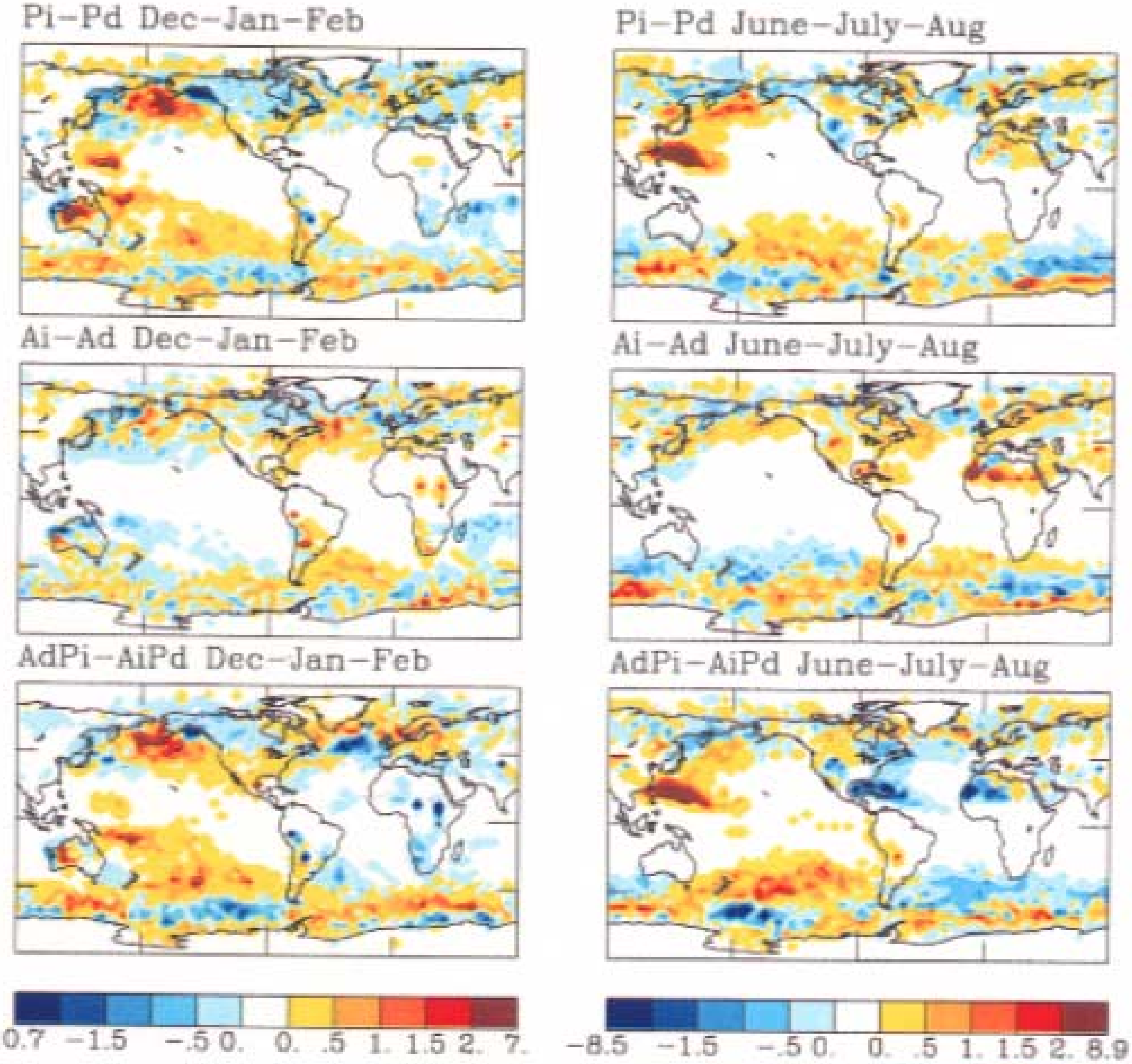


Fig. 2

Mean Intensity of Storms

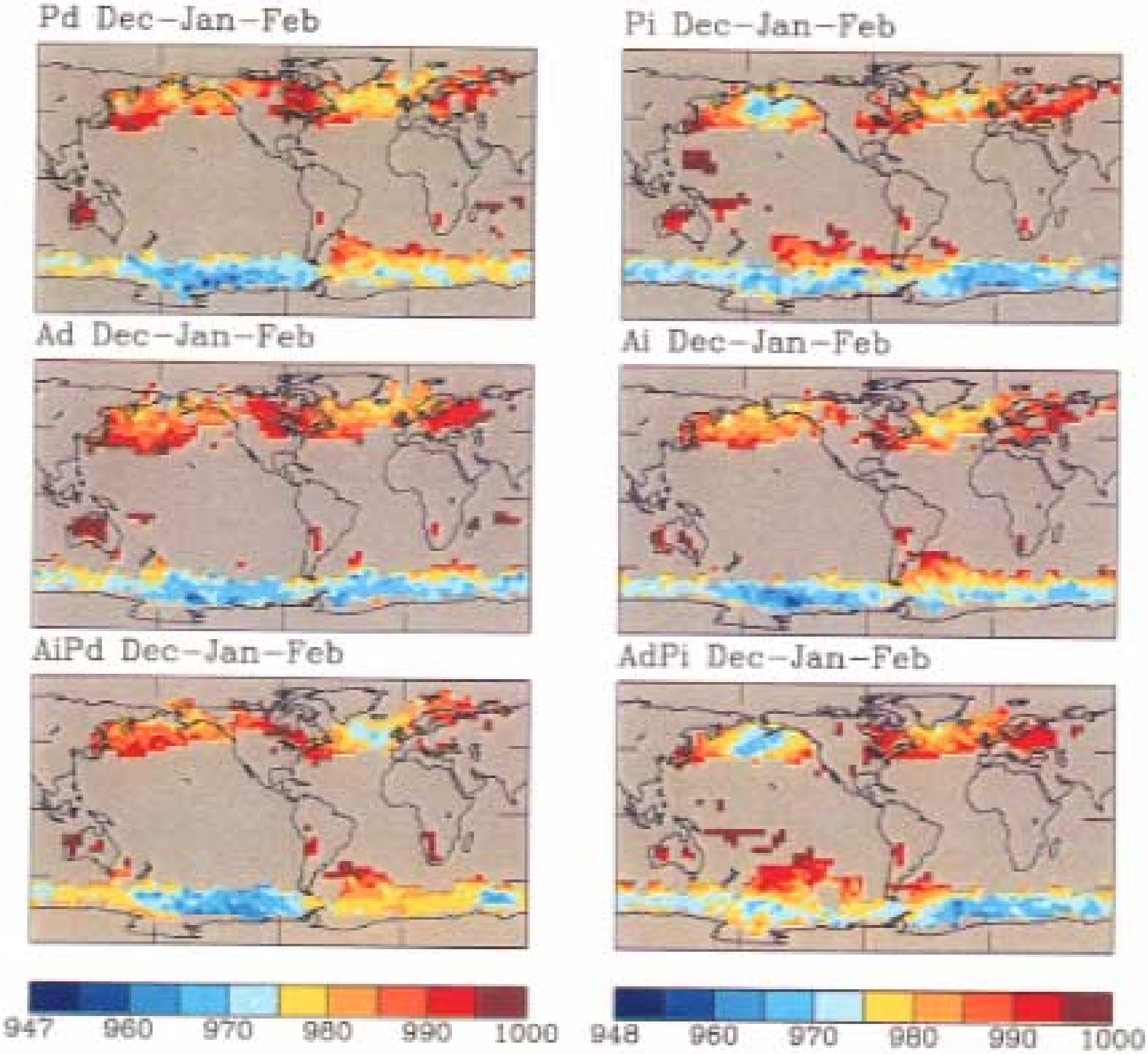


Fig. 3a

Mean Intensity of Storms

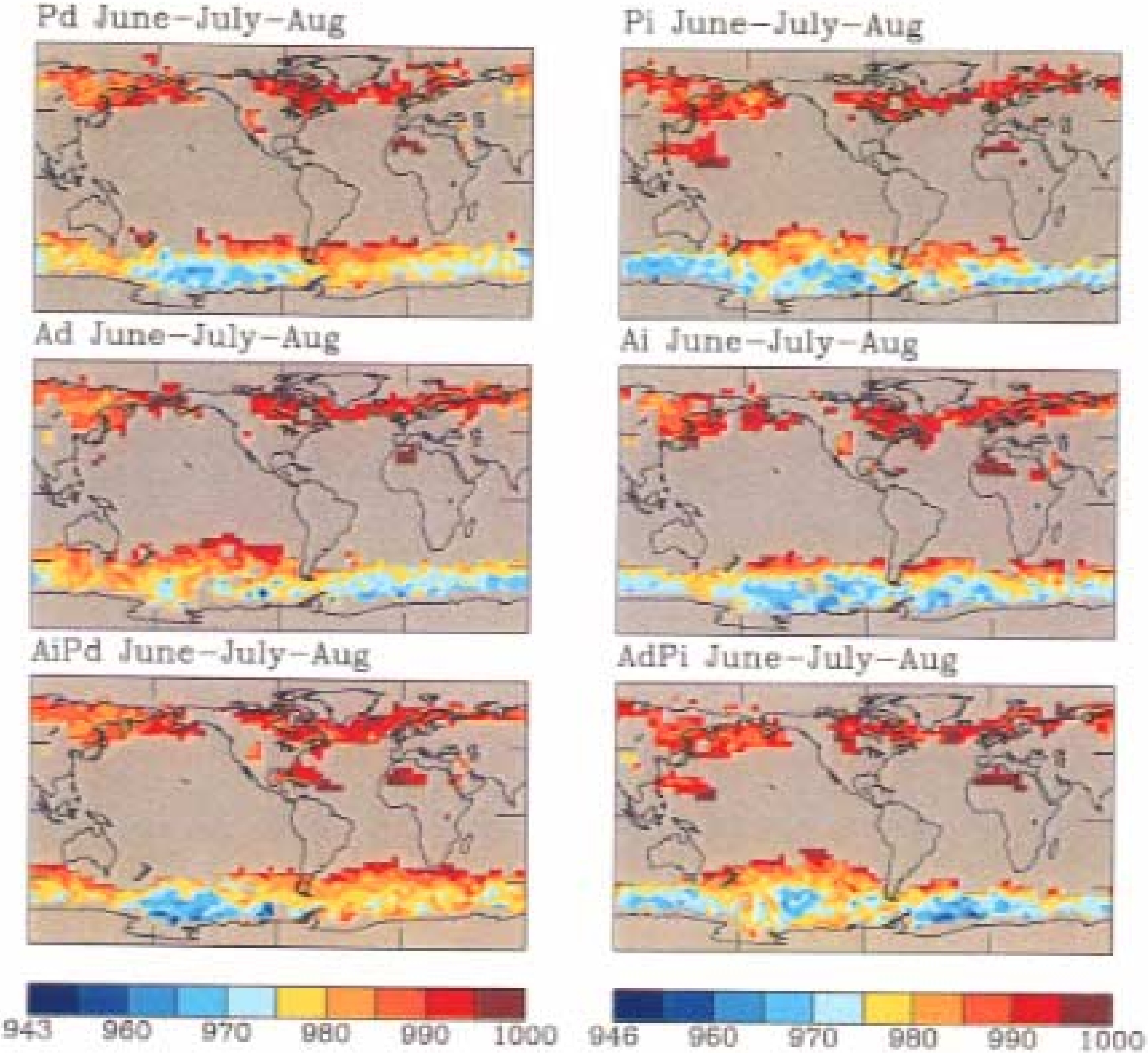


Fig. 3b

200 mb Wind (m/s) Dec-Jan-Feb

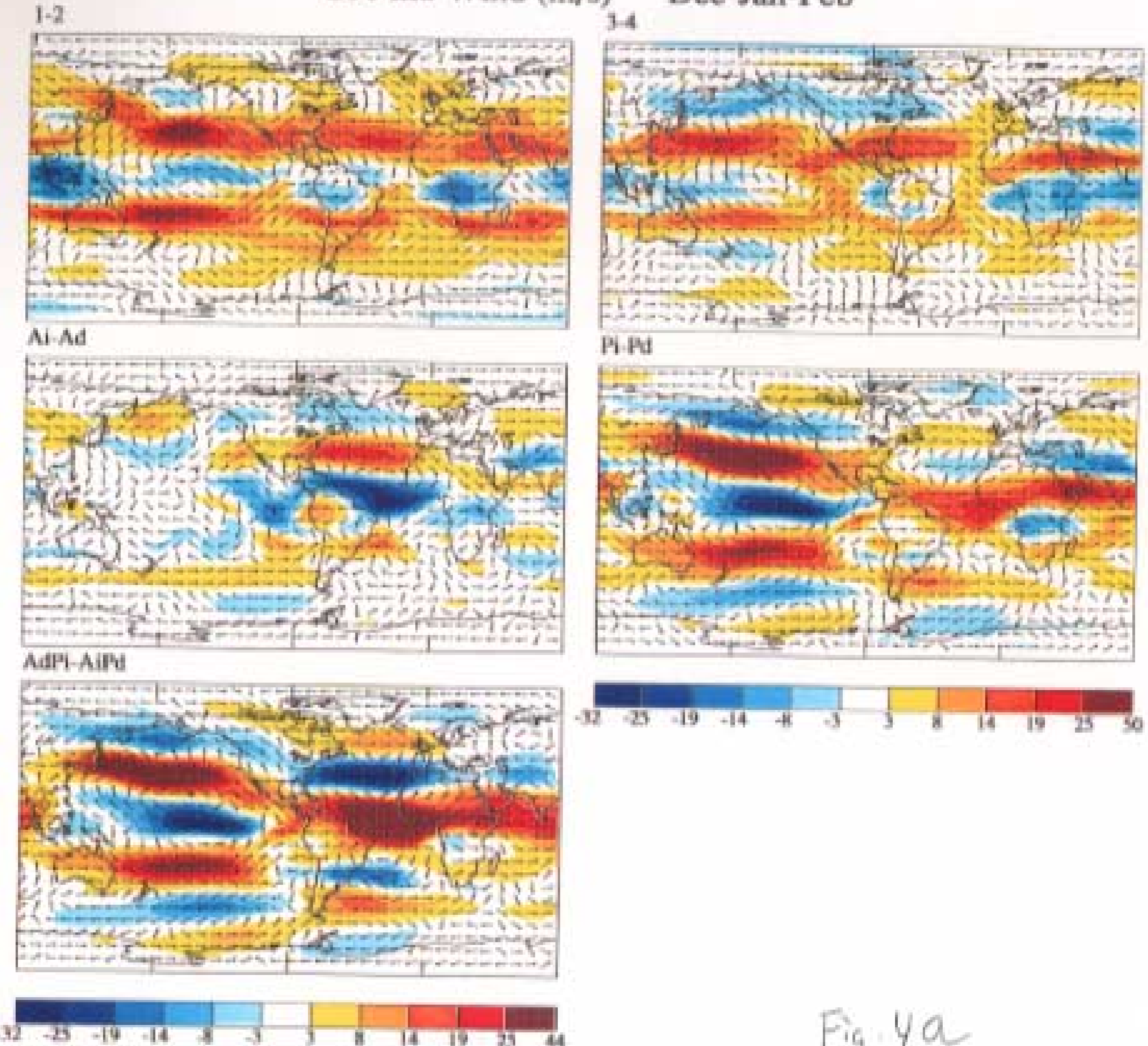


Fig. 4a

200 mb Wind (m/s) June-July-Aug

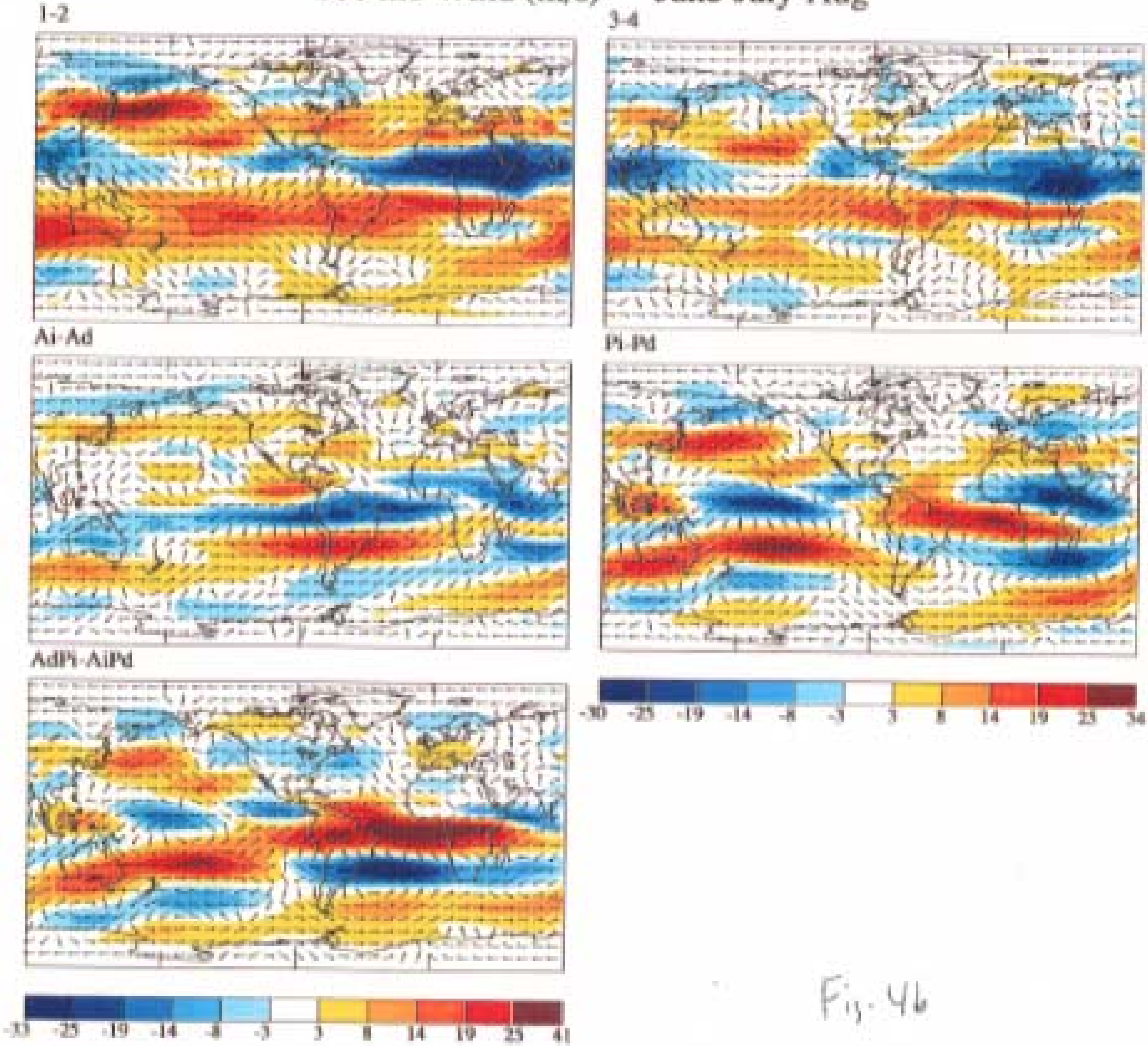
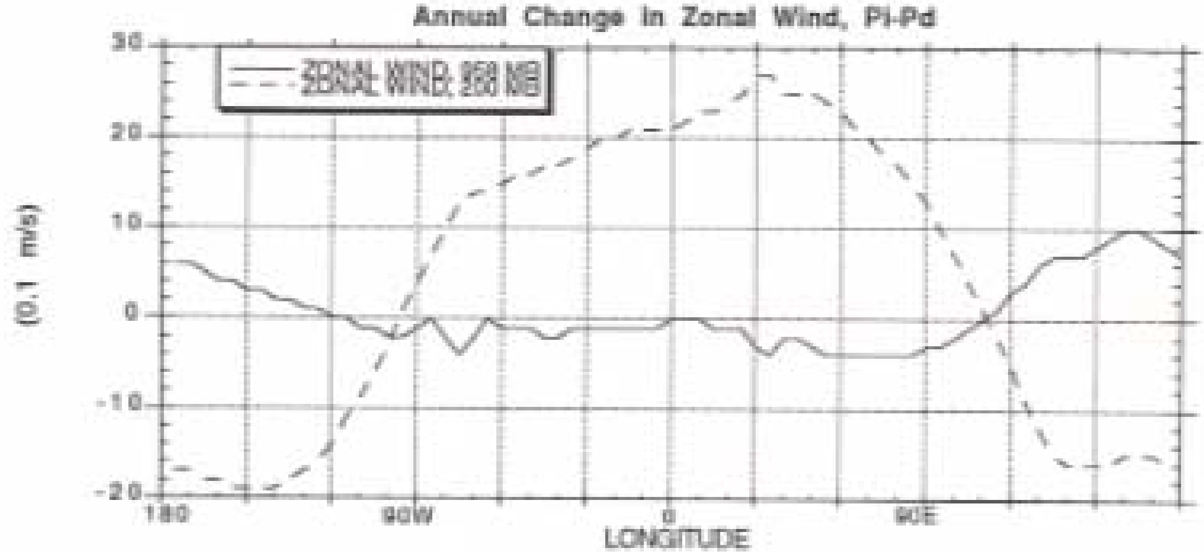
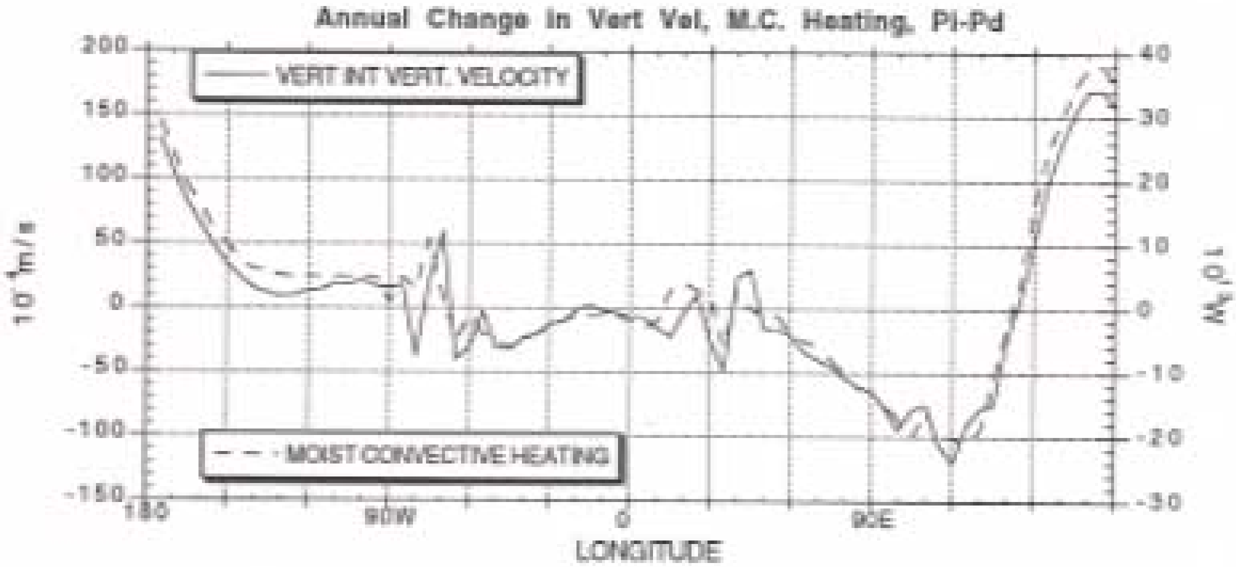


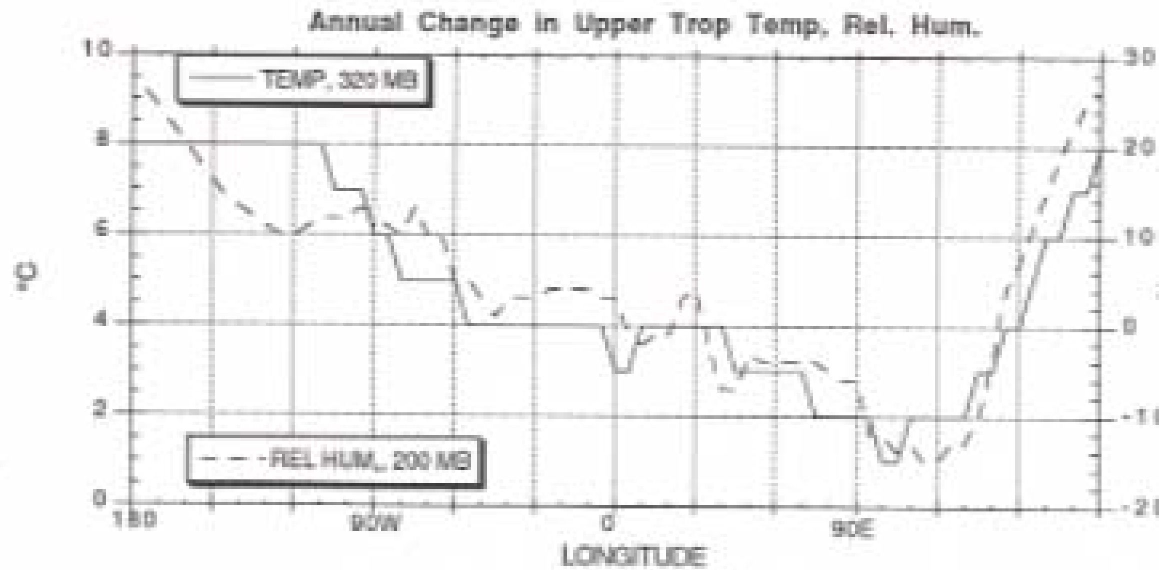
Fig. 4b



Annual Change in Zonal Wind, Pi-Pd
ZONAL WIND, 950 MB
ZONAL WIND, 200 MB
(0.1 m/s)
30
20
10
0
-10
-20
180
90W
0
90E
LONGITUDE

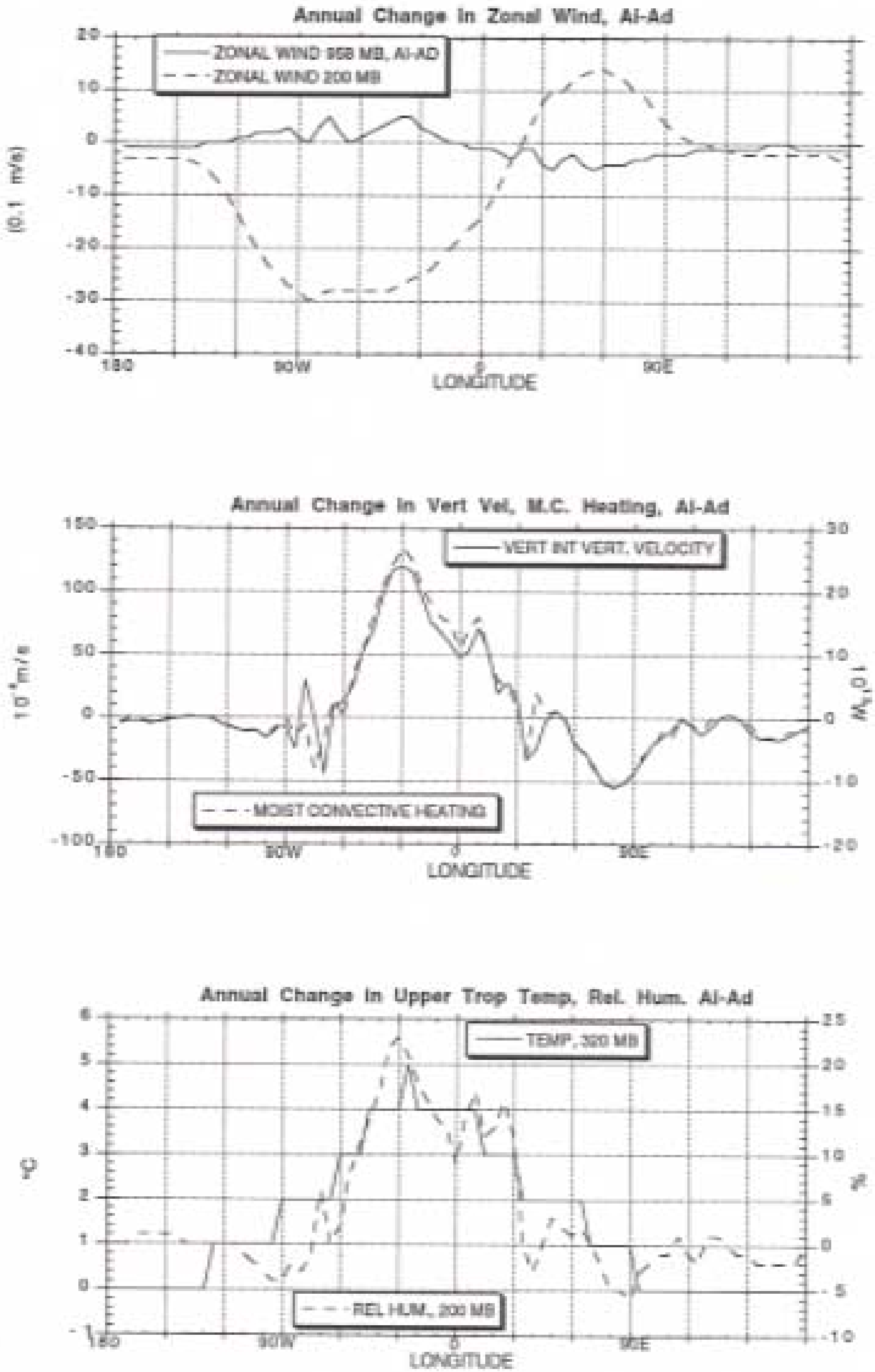


Annual Change in Vert Vel, M.C. Heating, Pi-Pd
VERT INT VERT. VELOCITY
MOIST CONVECTIVE HEATING
200
150
100
50
0
-50
-100
-150
40
30
20
10
0
-10
-20
-30
180
90W
0
90E
LONGITUDE



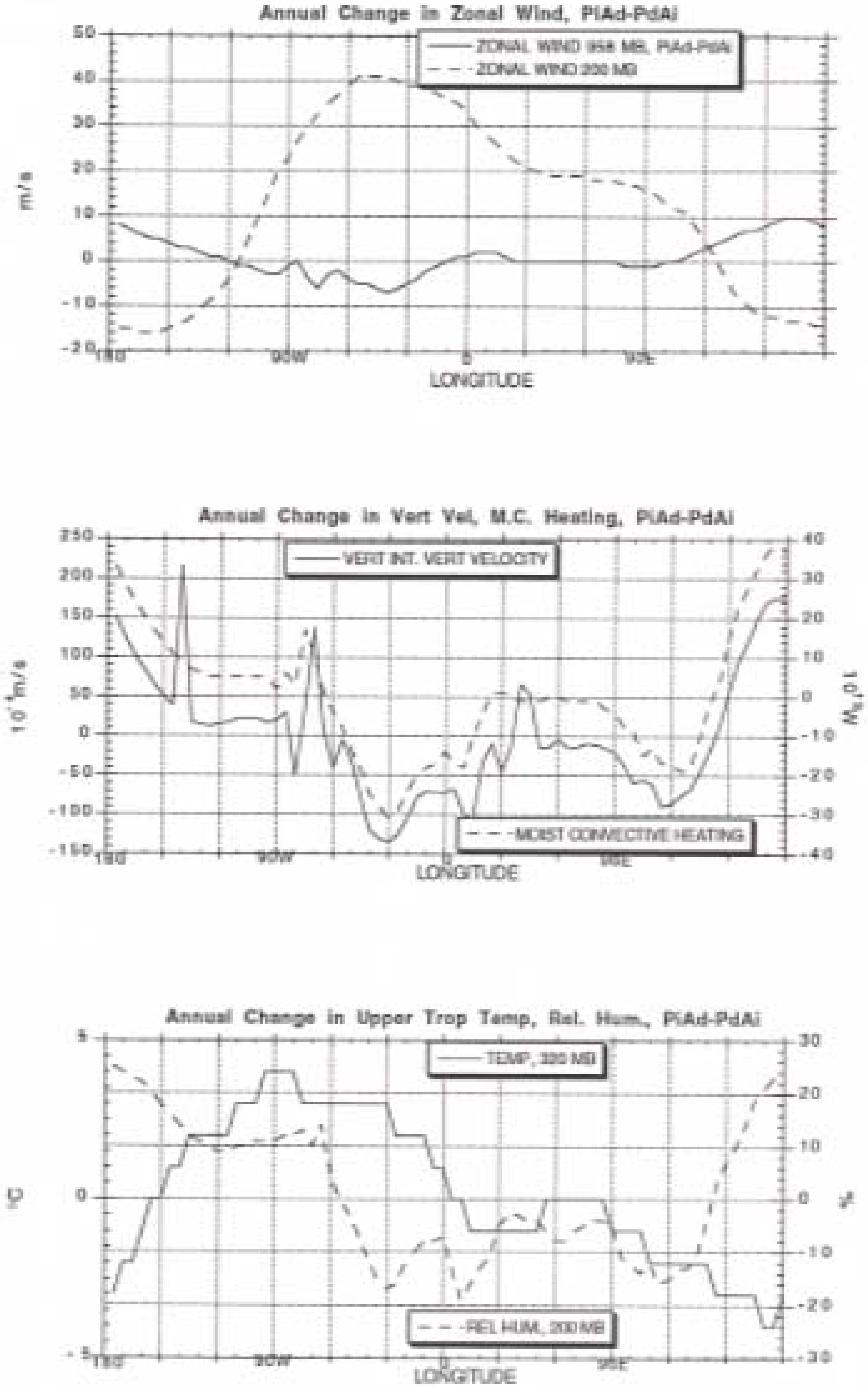
Annual Change in Upper Trop Temp, Rel. Hum.
TEMP, 320 MB
REL HUM., 200 MB
°C
%
10
8
6
4
2
0
30
20
10
0
-10
-20
180
90W
0
90E
LONGITUDE

Fig. 5



Annual Change in Zonal Wind, Al-Ad
ZONAL WIND 958 MB, Al-AD
ZONAL WIND 200 MB
(0.1 m/s)
LONGITUDE
180
90W
0
90E
Annual Change in Vert Vel, M.C. Heating, Al-Ad
VERT INT VERT. VELOCITY
MOIST CONVECTIVE HEATING
LONGITUDE
Annual Change in Upper Trop Temp, Rel. Hum. Al-Ad
TEMP, 320 MB
REL HUM, 200 MB
°C
%
LONGITUDE

Fig. 6



Annual Change in Zonal Wind, PiAd-PdAi
ZONAL WIND 200 MB
m/s
LONGITUDE
90W
0
90E
Annual Change in Vert Vel, M.C. Heating, PiAd-PdAi
VERT INT. VERT VELOCITY
MOIST CONVECTIVE HEATING
LONGITUDE
Annual Change in Upper Trop Temp, Rel. Hum., PiAd-PdAi
TEMP, 320 MB
REL HUM, 200 MB
°C
%
LONGITUDE

Fig. 7

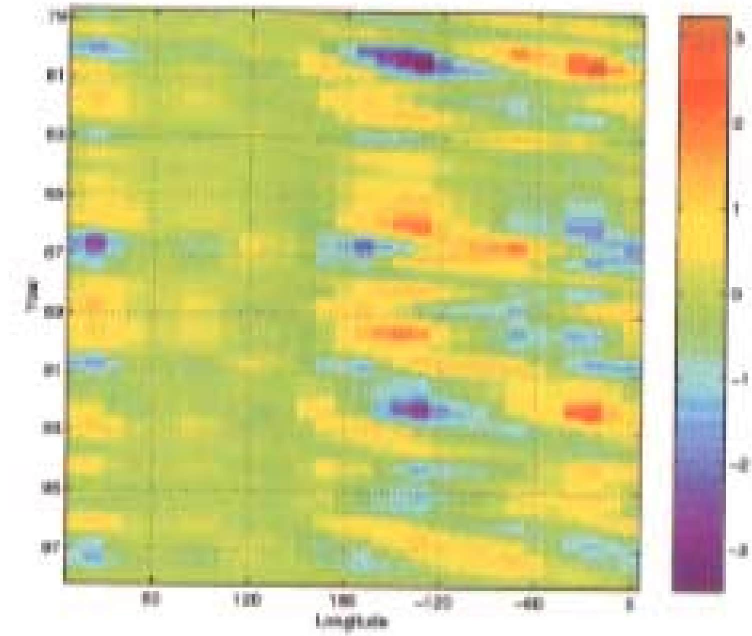


Fig. 8