



# **ANTARCTICA: BAROMETER OF CLIMATE CHANGE**

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## **Summary**

Antarctica plays a central role in global climate variability and change, but sustained efforts to illuminate its critical linkages to lower latitudes are lacking. A conjunction of new observational capabilities, advances in scientific understanding, and improving numerical models allow the question of the global relevance of Antarctica to be explored in detail for the first time. The first step is a comprehensive atmospheric study of the South Pacific sector of Antarctica (the SPAN project). This sector includes the Ross Sea region, an area that is closely coupled to the global atmosphere on a variety of time scales. Three aspects will be addressed: the forcing of the El Niño-Southern Oscillation phenomenon in Antarctica; the impacts of Antarctica on lower latitudes which are most pronounced over and adjacent to the western Pacific Ocean; and the testing and refinement near Ross Island (the RIME project) of coupled atmosphere-ice-ocean numerical models that are required for global simulations that realistically incorporate Antarctica.

## **1. Introduction**

We are on the threshold of the new millennium, confronted with unprecedented environmental and climatic dilemmas. The past few decades have witnessed an increasing societal awareness of our natural environment and the potential impacts of human civilization on global weather and climate. Foremost among these issues is the prospect of global environmental change. Humankind is faced with the possibility of catastrophic sea level rises associated with melting of even a small fraction of the Antarctic ice sheets. Although the validity of global change scenarios remains controversial, it has been established that the polar regions are sensitive indicators of climate change. In this respect, the Antarctic atmosphere remains an essential "test-tube" for meteorological processes as proposed by H. H. Lettau nearly 30 years ago.

Antarctica is the coldest, most remote continent on earth. At a mean elevation of 2300 m, it is by far the highest continent as well. Nearly the entire continent is covered with a permanent ice sheet that dominates the climate of the Antarctic atmosphere. The

continental area is 1.4 times that of the contiguous United States during austral summer but doubles in size during the winter due to the growth of sea ice around the continent. Nearly 75% of the world's fresh water is held in the vast Antarctic ice sheets. Meteorological studies of the Antarctic atmosphere are relatively recent. Although valuable data sets were obtained during the heroic expeditions of the early 20th century, routine meteorological observations from Antarctica commenced only in 1957 with the International Geophysical Year. Approximately 30 stations were established in the Antarctic region, all but six were situated near the coast. Surface and upper-air data taken at these stations provided the first comprehensive and systematic monitoring of the Antarctic atmosphere. Recently, manned station data have been supplemented significantly by data collected by automatic weather stations (AWS). Currently over 70 AWS exist over the continent, and given the advances in design and reliability of the AWS, additional deployments are likely. In addition, an impressive stream of data is available from polar orbiting satellites. The ongoing development of satellite-borne instrumentation and promise of novel remote sensing capabilities offer the exciting promise for additional observations of the Antarctic atmosphere during the next century.

Antarctic meteorology is at an important crossroads. In a real sense, recent and profound technological advances in observing capabilities now permit the challenge of global change issues to be confronted. Integrated observing strategies including conventional manned stations and upper air soundings, AWS networks and satellite-derived data sets provide a wealth of data on the Antarctic atmosphere at unprecedented time and space scales. In addition, mesoscale models (MM5, RAMS, NMS, etc.) containing elaborate and comprehensive physical representations of the atmosphere and underlying surfaces are available to the scientific community for a wide variety of numerical experiments. The availability of such observational and numerical tools will allow far more detailed physical process studies than ever before and is prerequisite before questions of global change can be addressed. Given the unique and important role of Antarctica in the global change arena, it seems essential that a comprehensive program be established with the long-term goal of documenting climate change and ultimately enabling an understanding of broad-scale impacts. Prerequisite to actual global change programs, detailed interdisciplinary process studies must be conducted to examine the interaction of the coupled Antarctic atmosphere/ice/ocean system with the lower latitude climate system. Given the available logistical support in the Ross Sea sector and the documented global importance of this region on synoptic and longer time scales, it seems logical to conduct the first intensive study in this region of Antarctica.

## **2. Outstanding Issues**

### **a. Atmospheric variability**

The atmosphere varies on a wide range of space and time scales, and this variability represents the signature of climatic phenomena on Antarctica. The variability characteristics of temperature, circulation, cloud cover, precipitation, etc., are not well known for Antarctica because of limited analysis of the new data sources. This

knowledge is required to understand and model climate variability and change. This shortcoming is being alleviated by atmospheric numerical reanalyses that blend observations with short-term numerical weather forecasts, and span the last 40 years. Significant and socially relevant climatic variations also exist on interannual time scales. The recent El Niño of 1997-98 is one such example. Analyses clearly show a marked perturbation in the seasonal cycle of surface pressure over Antarctica. Each year, dramatic changes in surface pressure result during transition seasons from September to December and January to April. Accompanying the rapid springtime warming, atmospheric mass becomes transported southward and surface pressures rise over Antarctica, consistent with the warming of the atmosphere. The process reverses itself during the austral autumn period.

Figure 1 illustrates the surface pressure changes during the austral springtime period from September to December based on a 30-year record (1960-89) taken from the recent National Centers for Environmental Prediction (NCEP)/ National Center for Atmospheric Research (NCAR) reanalysis effort. The greatest increase in surface pressure is seen atop the Antarctic interior, and the contours of surface pressure change follow the terrain contours. By contrast, the 1997-98 El Niño episode modulated significantly the seasonal pressure changes. Figure 2 illustrates the changes in surface pressure from September to December 1997 from the NCEP operational analyses. The area of the austral springtime surface pressure increase is considerably larger than the climatological norm. In addition, anomalously large increases occurred in the Ross Sea sector during the El Niño period. This is a reflection of the enhanced synoptic activity in the eastern Ross Sea during the late winter period. Investigations have shown the El Niño-Southern Oscillation (ENSO) signal to be clearly detectable in the Antarctic. The teleconnections between Antarctica and the tropical latitudes need to be understood before realistic studies of longer term global change issues can be investigated.

#### **b. Antarctic heat sink**

The higher latitudes of the Southern Hemisphere, including the ice sheet and the surrounding sea ice zone, constitute one of the two primary areas on earth where there is net loss of energy from the atmosphere to free space. Recent studies with global climate models (GCM) have suggested that the hemispheric and global atmospheric circulations are sensitive to modest changes in the temperature of the Antarctic atmosphere. The extent, phase and properties of clouds play a critical role in the atmospheric heat sink, but these characteristics have not been established for Antarctica. In a similar fashion, sea ice extent and concentration exert a major control on remote climate. As an extreme example, Figure 3 shows that a GCM sensitivity study, where all sea ice is removed from around Antarctica throughout the year and replaced by open water, has a major impact on the monsoon precipitation over China during early fall (in the Northern Hemisphere). This modeling result is supported by an observational analysis that related observed changes in Antarctic sea ice extent to measured variations in Chinese monsoon precipitation and runoff. This observational work indicates that the extreme GCM experiment captured a real atmospheric phenomenon and furthermore suggests that the most important sea ice changes occur in the Ross Sea sector. The atmospheric

mechanisms by which Antarctica affects remote climate are poorly understood and require systematic study.

### **c. Terrain forcing**

The extensive and elevated ice sheet dominates the behavior of the Antarctic atmosphere. This is evident in the climatic fields of all atmospheric variables. The katabatic wind regime is a consequence of the radiative cooling of the Antarctic ice slopes, and is closely coupled to the behavior of the overlying atmosphere. The degree of synoptic control of the katabatic wind variability is incompletely understood and is central to the response of the Antarctic atmosphere to external forcing. Diagnostic studies have revealed that export of cold air from Antarctica via the katabatic wind regime can lead to large pressure changes over the continent on both synoptic and seasonal time scales with compensating changes taking place at much lower latitudes. As an example, Figure 4 shows zonally-averaged the impact of surface pressure changes due to synoptic scale processes over a four-day period from 00 UTC 28 June to 00 UTC 2 July 1988. The decreases in surface pressures over Antarctica reflect a strong katabatic transport in the lower atmosphere through the Ross Sea sector. Compensating surface pressure rises are seen at middle-to-lower latitudes in the Southern Hemisphere. Surface pressure changes extend nearly to the tropical latitudes of the Southern Hemisphere. The impact of such latitudinal mass exchanges on the circulation of entire Southern Hemisphere could be substantial and has yet to be unexplored.

### **d. Atmospheric water budget and global sea level**

The net water exchange between the Antarctic ice sheet and the ocean is uncertain, but could contribute substantially to the current rise of global sea level, about 2 mm/yr. Precipitation is the primary water input to the ice sheet; this can change essentially instantaneously in response to climate variability, and determines the short-term ice sheet response to this change. For example, Figure 5 shows that the ENSO phenomenon has a strong in-phase and anti-phase relation to the precipitation (actually P-E) over the Marie Byrd Land part of West Antarctica, following from the changes in cyclonic activity evidenced by Figure 2. Although only a small fraction of precipitation appears to be lost to the ocean in the form of blowing snow, this phenomenon could be important to the behavior of the katabatic winds. Sublimation from the surface to the atmosphere is larger than previously thought, and for certain regions is the dominant component of annual snow accumulation. The moisture source for Antarctic precipitation is uncertain, but appears to determine the stable isotopic content of snowfall. When ultimately extracted from the ice sheet as an ice core, this signature is the primary paleoclimatic proxy variable (for temperature), and is typically interpreted on the basis of regression analysis rather than the governing physics.

### **e. Antarctica as a unique natural laboratory**

In addition to being the coldest, highest, driest, and windiest continent on earth, Antarctica has a number of other unique atmospheric characteristics. The stability of the

boundary layer is unprecedented in horizontal extent and temporal persistence, and could be used to explore the dynamics of the atmosphere in this little-explored, but important stability range. The temperature and humidity conditions at the surface are similar to the global upper troposphere, a region of the atmosphere that is important for infrared energy loss to space. Clouds near the surface of the ice sheet represent the cold, dry and pristine extremes of this formation process. Easy and routine ground-based access to such clouds can yield a comprehensive depiction of cirrus cloud behavior which is not readily obtainable otherwise. Monitoring of the Antarctic atmosphere and precipitation for chemical constituents has provided the background global level and trends of many contaminants. Study is also needed of the transfer of the atmospheric chemical signals into the snowpack to enable more quantitative use of ice core records.

#### **f. Ocean-atmosphere interaction**

At maximum extent, the Antarctic sea ice cover effectively doubles the continental area. The exchange of heat and moisture between the ocean and atmosphere is strongly modulated by sea ice, as is the momentum coupling between the two media. Further efforts are needed to understand the interactions of ice, ocean and atmosphere in the very dynamic environment of the Antarctic sea ice zone, particularly how the cyclonic forcing becomes modified over sea ice. Close to the coast, offshore winds generate reduced ice concentration areas, which are sites of intense heat loss to the atmosphere and vigorous ice formation and which are of importance to the biota. The near-coastal ice generation and brine rejection contribute to the formation of Antarctic bottom water, the densest water in the global ocean that couples Antarctica to the rest of the planet.

In summary, Antarctica is the primary heat sink in the global climate system, and plays an important role in climate change and variability. Projections of the state of global change (e.g., global warming) must accurately account for Antarctic atmospheric processes whose effects are transmitted to the rest of the planet via the atmosphere and the ocean. In particular, the deep ocean simulation depends critically on Antarctic atmospheric conditions and needs proper physical representation in climate system models.

### **3. Course of Action - South Pacific-Antarctic Meteorology Study (SPAN)**

It is time for a better assessment of the roles of Antarctic atmospheric processes in hemispheric and global scale circulations. The first step is the initiation of a comprehensive study of the South Pacific sector of the Antarctic (140°E to 60°W). This region is coupled with lower latitudes (e.g., via the ENSO phenomenon, Figures 2 and 5), and exhibits the largest interannual variability. The emerging view is that this area may be of pivotal significance for global climate variability and change. This sector is also logistically accessible by the U.S. Antarctic Program, and is characterized by strong international collaborations with France, Italy, and the United Kingdom. The South Pacific-Antarctic meteorology study (the SPAN project) will concentrate on three aspects: the impacts of the tropics on Antarctica through consideration of ENSO; the impacts of Antarctica on lower latitudes; and the testing and refinement of coupled

atmosphere-ice-ocean numerical models that are required for global change studies that realistically include Antarctica. Each of these aspects is explored in more detail below.

**\* Forcing of ENSO Variability in Antarctica**

Figure 5 shows that the ENSO signal in West Antarctica is strong but variable, and cannot simply result from sea surface temperature changes in the tropical South Pacific Ocean whose Antarctic influences should be fairly repeatable. Previous analysis strongly suggests that midtropospheric ridging over Wilkes Land in East Antarctica is closely tied to the fluctuations in the Amundsen Sea low which lead to the precipitation variations depicted by Figure 5. Diagnostic and modeling studies as well as field investigations are needed to understand the interactive synoptic and boundary layer processes in both East and West Antarctica that lead to the variable ENSO signal in West Antarctica, and how these are linked to sea surface temperature variations in the tropical Pacific and Indian Oceans. In particular, targeted deployments of AWS will be needed to document and understand the spatially complex ENSO signal over West and East Antarctica.

**\* Antarctic Influences on Lower Latitudes**

Figures 3 and 4 illustrate the impact of Ross Sea sector processes on remote atmospheric behavior on synoptic and interannual time scales. Both of these likely involve modulation of the circumpolar vortex that is centered over the Ross Ice Shelf in the midtroposphere. The unknown mechanisms by which this modulation takes place can be explored by diagnostic and modeling studies and by targeted aircraft campaigns to understand vortex behavior in critical areas. The propagation of the influences northward from the Ross Sea and their interaction with lower latitude circulations have barely been investigated. These topics could take advantage of the recently available reanalyses from NCEP/NCAR and the European Centre for Medium-Range Weather Forecasts that span up to 40 years. GCMs, in conjunction with emerging observational data sets, can be used to study the sensitivity of global climate to anomalous surface and atmospheric forcings in the Ross Sea sector and to illuminate the lower latitude impacts of Antarctica which seem to be most pronounced in the western Pacific Ocean.

**\* Ross Island Meteorology Experiment (RIME)**

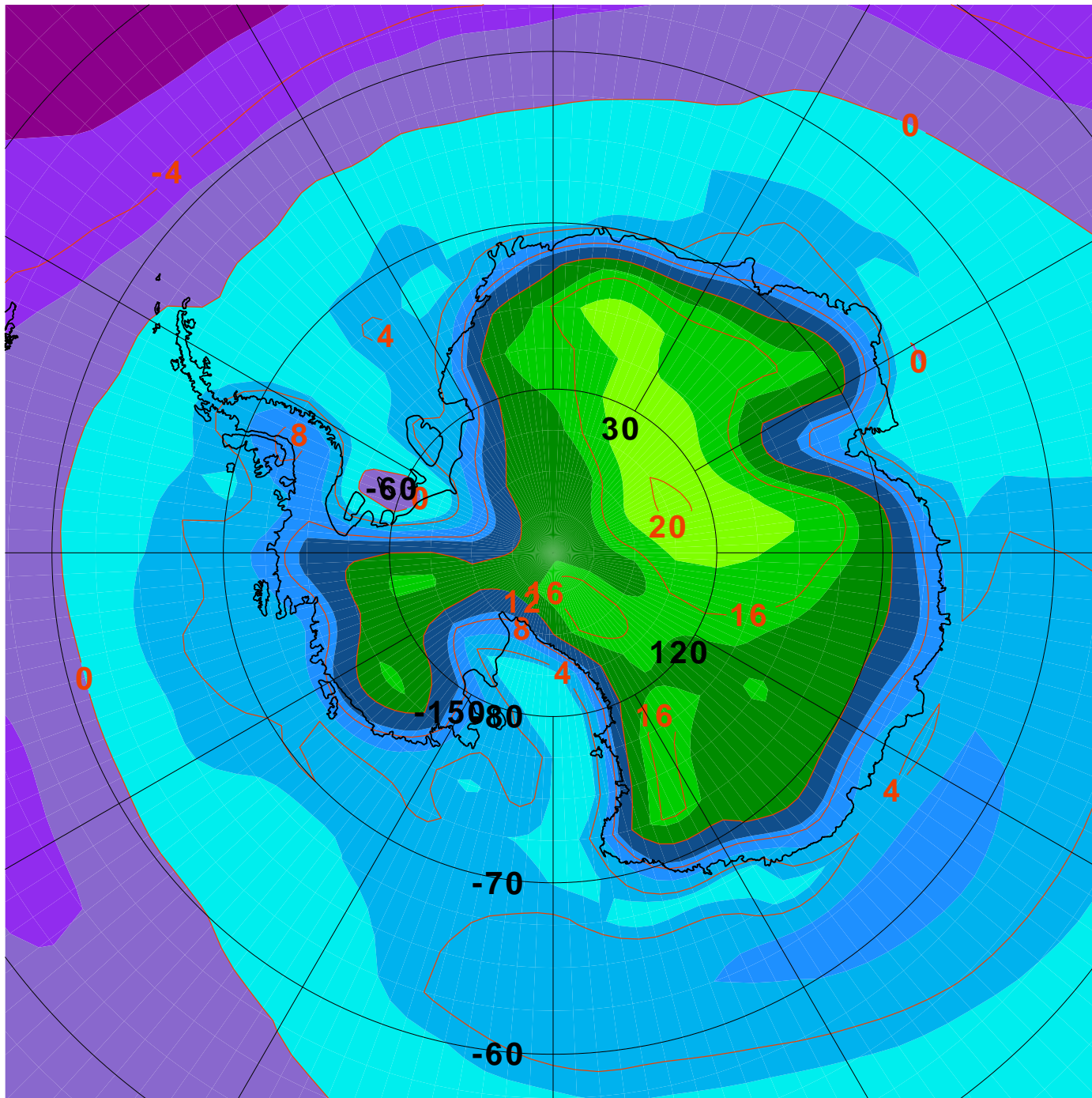
The Ross Island area is subject to a wide variety of stable boundary layer phenomena and is adjacent to the Ross Sea. A large polynya is located off the northwestern edge of the Ross Ice Shelf, where a wide variety of air-ice-ocean interactions take place. Extreme topographic forcing is a notable characteristic of the area. McMurdo Station on Ross Island, being the main logistics base for U.S. operations in Antarctica, is already surrounded by a detailed meteorological network which could be enhanced with modest effort. This could involve the temporary deployment of ground-based remote sensing equipment including state-of-the-art profilers of temperature, humidity and winds. Comprehensive satellite observations are already archived at McMurdo. Airborne sampling of clouds, chemical constituents, and circulation

characteristics can be supported from the local airfields, and ship campaigns can be staged from the port. It is proposed to conduct an in-depth observational and modeling project for the Ross Island area (the RIME project) directed toward the development and testing of parameterizations for air-ice-ocean models that are required for global change simulations which realistically incorporate the Antarctic heat sink. An additional benefit will be higher quality weather forecasting support for U.S. operations at Ross Island.

To summarize, the development of the SPAN project is proposed that will address the atmospheric interactions between Antarctica and lower latitudes. This will involve field work (the RIME project), analysis and modeling aspects. International scientific cooperation and data exchange will be featured. Educational opportunities will be created that will ultimately produce the next generation of scientists interested in Antarctica and how this area participates in global climate variability and change.

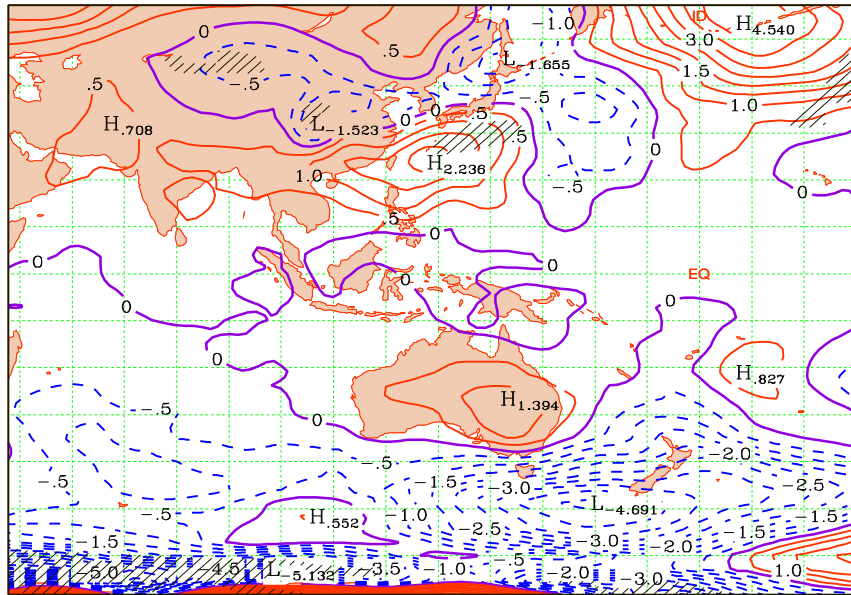
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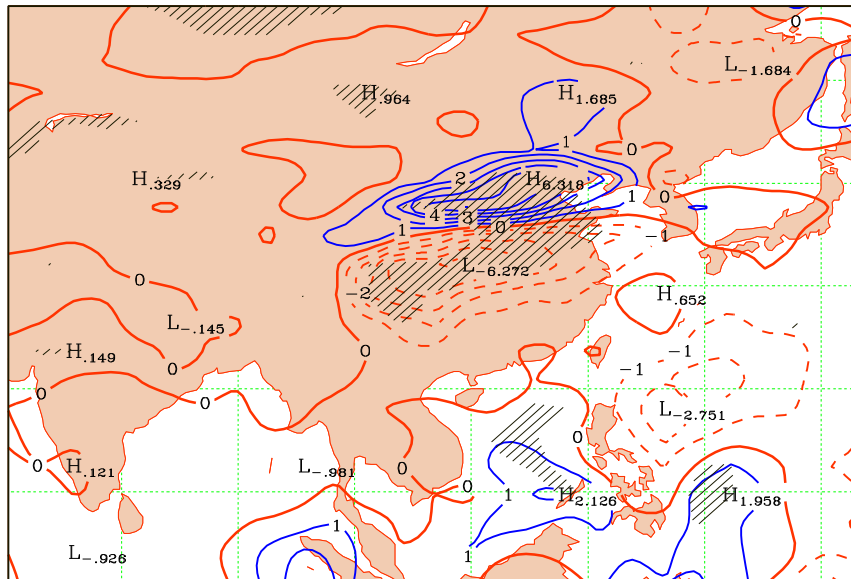


### Surface Pressure Difference (hPa) During September



CONTOUR FROM -6.5 TO 5 BY 0.5

### Large-Scale Precipitation (cm) During September



CONTOUR FROM -6 TO 6 BY 1

**Figure 3. Results of NCAR CCM2 simulations showing meteorological connection from the Ross Sea to monsoon precipitation over China during September. (a) Surface pressure difference (hPa), and (b) Large-scale precipitation (cm). Differences are between simulations without any Antarctic sea ice and with climatological sea ice. Statistically significant areas (hatching) show increased precipitation over northern China and decreased precipitation over central China, very similar to the finding of an observational study.**

### Surface Pressure Changes

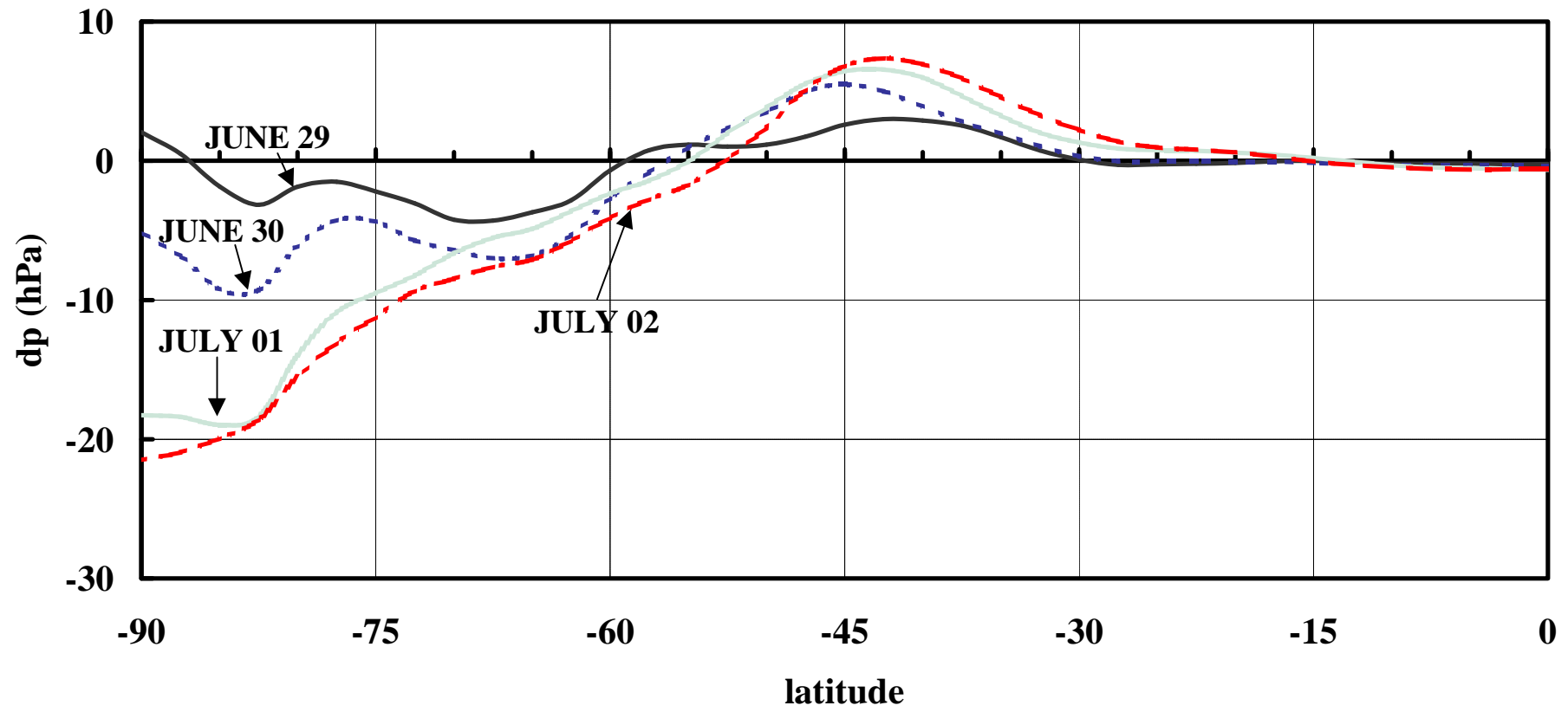
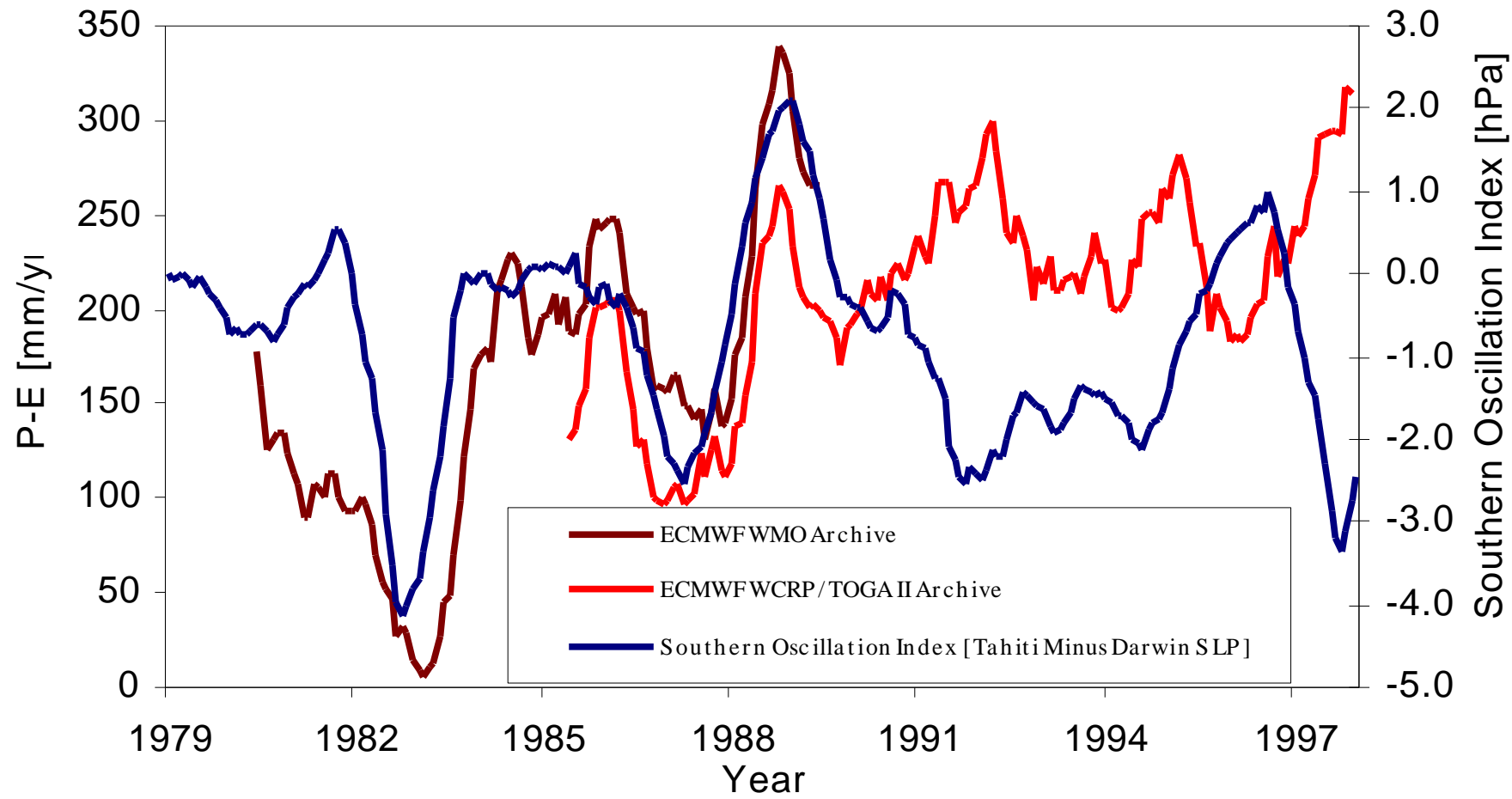


Figure 4. Zonally-averaged surface pressure differences from 00UTC 28 June 1988.



**Figure 5. Comparison of precipitation minus evaporation for South Pacific Sector 120°W - 180°, 75°S - 90°S and Southern Oscillation Index (annual running means). The series are correlated from 1982 to 1990. After 1990, the relationship between the series rapidly switches to become anticorrelated, a relationship that exists through 1998.**