Seasonal Variations of Tropospheric Wind over Indonesia:
Comparison between Collected Operational Rawinsonde Data and
NCEP Reanalysis for 1992–99

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Abstract

Seasonal variations of wind in the troposphere are analyzed based on operational rawinsondes at 11 stations over Indonesia for 1992–1999 and the results are compared with NCEP reanalysis. For meridional wind, an annual oscillation caused by north-south shift of a meridional (Hadley-type) circulation is clearly found. Winter-poleward flow of the upper-tropospheric meridional circulation is stronger than summer-poleward flow. The winter (southern) hemispheric cell in northern summer has a larger invasion across the equator (as suggested in the zonal-mean Hadley cell), and weaker meridional flows than the winter (northern) hemispheric cell in northern winter. Along the boundary of twin meridional circulation cells, a zonal (Walker-type) circulation seems to exist, and has easterly (westerly) wind in the

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upper (lower) troposphere in the Indonesian region. The zonal circulation is also shifted from the equator associated with the meridional circulation cell boundary. However, a semiannual oscillation, which has easterly maxima in January–February and July–August is more clearly observed in the upper-tropospheric zonal wind, which is consistent with a consideration on conservation of absolute angular momentum for the upper-tropospheric winter-poleward (equatorward) air mass transport associated with the winter-hemispheric meridional circulation cell, invading the summer hemisphere across the equator.

In comparison with the seasonal-vertical variations based on the operational rawinsonde data, the NCEP reanalysis seems to overestimate the upper-tropospheric northerly and easterly maxima during northern summer. In other words, the NCEP reanalysis produces a winter hemispheric side meridional circulation cell with similar intensities between both solstitial seasons, in spite that in the operational rawinsonde data the winter hemispheric side meridional circulation cell in northern summer is weaker than that in northern winter. The overestimation of easterly may also be related with an insufficient reproduction of the winter-hemispheric meridional circulation cell—such as too large northward invasion.

1. Introduction

Climate in the tropics has been studied mainly by surface meteorological observations, satellite cloud imageries and/or products of objective analysis (e.g., Murakami and Matsu- moto 1994). Satellite cloud imageries can cover vast fields, but have limitations for grasping three-dimensional structures. Objective analysis may provide wind and temperature fields in the troposphere and lower stratosphere, but they are considered to be less reliable in the vicinity of the equator, mainly due to invalidity of geostrophic approximation, and scarcity of aerological observations. For India, and the north-western and southeastern Pacific regions (east of about 130°E), Hartmann and Gross (1988) analyzed the annual variations of 200- and 850-hPa zonal winds based on operational rawinsonde data. In the central and eastern Pacific, tropospheric wind observed continuously by the Trans-Pacific Profiler Network has shown that annual variation of zonal wind is quite different at each station (Piura, Christmas Island, Pohnpei and Biak), and that it is strongest during La Niña, and weakest during El Niño at Christmas Island (Gage et al. 1994, 1996). In global climate studies by zonal-mean description, Oort and Yienger (1996) have discussed seasonal intensity of Hadley circulation on the basis of operational rawinsonde data, except for data around the Indonesian maritime continent. For vertical distributions of wind variations over Indonesia, a wind profiler station has been constructed near Jakarta (see Subsection 2.3), and several case studies have been done: a convection center passage at the beginning of rainy season (Hashiguchi et al. 1995b), a mixed Rossby-gravity wave activity in the rainy season (Widiatmi et al. 1999, 2001), and others. Much longer-period data analysis has also been done (H. Hashiguchi, private communication), and striking year-to-year variations have been found, although these results have not been published.

Concerning the definition of Hadley circulation, original depiction is a simple atmospheric circulation with an upward flow over the equator, and downward flow at higher latitudes caused by latitudinal heat gradient in each hemisphere, and structure of the Hadley circulation is homogeneous in zonal direction (zonal mean circulation). However, local circulations in the meridional-vertical plane has been called various names—such as north-south circulation (Young 1987), Hadley-type circulation (Young 1987; Shukla 1987), local Hadley circulation and local meridional circulation (Webster 1987; Murakami 1987), in spite that the driving reason of the local circulations are the same with that of the Hadley circulation. In a similar manner, longitudinal circulation resulted from the gradient of sea surface temperature along the equator in the Pacific Ocean is called the Walker circulation, but other circulations in zonal-vertical plane in other longitudinal sections are called east-west or Walker type circulation (Krishnamurti 1971; Young 1987; Web- ster 1987) (Sometimes the Walker circulation itself is expressed as a east-west circulation). In a monsoon view point, Webster et al. (1998) considered that Asian-Australian monsoon con-
sists of three major circulations, and called them lateral monsoon, transverse monsoon and Walker circulation.

In this study, operational rawinsonde data is collected for about seven years (November 1991–May 1999), and have made a reliability check for scientific analyses and discussions. In addition, fundamental analysis is made to reveal seasonal variations and spatial structure of wind in the whole troposphere (below about 20 km altitude) over Indonesia, based on the operational rawinsonde data, as well as NCEP (National Centers for Environmental Prediction of the United States) rawinsonde archive. We have also compared them with objective analysis (NCEP reanalysis) data, to discuss significance of operational rawinsonde data over Indonesia in comparison with NCEP reanalysis data. In Section 7 the conclusions are summarized.

2. Data and analysis methods

2.1 Operational rawinsonde data over Indonesia

Indonesian Meteorological and Geophysical Agency (BMG) operationally conducts almost daily (at some stations twice a day, or bидaily) rawinsonde observations at 11 stations\(^3\). Location and rawinsonde system of each station are shown in Fig. 1, and Table 1. Data transmis-

\(^3\) There are 12 stations including Merauke (8.46°S, 140.38°E), but the Merauke station is omitted in this study because observation had not been conducted in the analysis period.
sion procedures inside Indonesia for the analysis period of this study (until May 1999) are as follows. First, after observation, each station prepares telex format data (TEMP and PILOT reports). At Jakarta station, the telex data are made automatically, but at other stations operators make them manually by reading values at standard and significant levels from a plotted profile. Then, the data are sent to a regional center by telex. There are five regional centers in Indonesia (Medan, Jakarta, Denpasar, Ujung Pandang and Jayapura), and the data received at each regional center are forwarded to AMSC (automatic message switching center) of the BMG headquarters at Jakarta. At AMSC, operators input the data into a computer, and sent them to outside of Indonesia (Singapore or Melbourne), through GTS (global telecommunication system). However, transmission of data is not always perfect because of an artificial error occurred in above-mentioned procedures. Report of the data for GTS often out of time, too. BMG Jakarta and the other 10 stations keep original data, but most of them are written in a paper form. These original rawinsonde data are collected by ourselves (hereafter, the BMG data), and in this paper daily observation data are used (mostly at 00 UTC) from November 1991 to May 1999. Many missing data or periods are included without observations, for example more than one year at Ambon.

Data quality is checked. The data are at both standard pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20 and 10 hPa), and significant levels. There are some duplicated data with different values, probably because some errors might occur in digitizing the data. Such different duplicated data are checked carefully and they are not used for data analysis. In this study the data are used at standard pressure levels at 00 UTC, and have omitted data with wind speed exceeding 100 m/s in the absolute value, or exceeding 60 m/s in the difference from the total mean value over the whole analyzed period at each level at each station. Monthly mean data sets (to be used in Section 4) have been calculated from the daily data after these quality check procedures. In order to recover lacked data and also to filter out day-to-day variations, we have made pentad (five-day) mean data sets at each year, at each standard pressure level, and at each station, as long as observation was done at least one time for a five-day period. Data on February 29 of a leap year have been omitted. By this pentad-mean procedure some equatorial wave-like components such as two- or four-day period modes (cf., Takayabu and Nitta 1993; Sato et al. 1994; Widiyatmi et al. 1999, 2001) may be almost filtered out. Furthermore, the intraseasonal variations with 30- to 60-day periods have been removed from the pentad mean

<table>
<thead>
<tr>
<th>Station</th>
<th>Lat. (°N)</th>
<th>Long. (°E)</th>
<th>Elv. (m)</th>
<th>Rawinsonde system¹</th>
<th>Period</th>
<th>Data rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Padang</td>
<td>−0.88</td>
<td>100.35</td>
<td>3</td>
<td>Meisei manual</td>
<td>11 Apr 1992–21 May 1999</td>
<td>42.8</td>
</tr>
<tr>
<td>Pangkal Pinang</td>
<td>2.17</td>
<td>106.13</td>
<td>33</td>
<td>Meisei manual</td>
<td>3 Apr 1992–3 May 1999</td>
<td>37.8</td>
</tr>
<tr>
<td>Surabaya</td>
<td>−7.22</td>
<td>112.72</td>
<td>58</td>
<td>VIZ manual</td>
<td>5 Apr 1992–21 May 1999</td>
<td>48.9</td>
</tr>
<tr>
<td>Manado</td>
<td>1.53</td>
<td>124.92</td>
<td>80</td>
<td>VIZ manual</td>
<td>17 Feb 1992–15 Dec 1998</td>
<td>43.4</td>
</tr>
<tr>
<td>Palu</td>
<td>−0.68</td>
<td>119.73</td>
<td>6</td>
<td>Meisei manual</td>
<td>20 Jun 1992–21 May 1999</td>
<td>49.3</td>
</tr>
<tr>
<td>Ujung Pandang¹</td>
<td>−5.07</td>
<td>119.55</td>
<td>14</td>
<td>VIZ manual</td>
<td>5 Apr 1992–21 May 1999</td>
<td>45.8</td>
</tr>
<tr>
<td>Kupang</td>
<td>−10.16</td>
<td>123.67</td>
<td>108</td>
<td>VIZ manual</td>
<td>3 May 1992–1 May 1999</td>
<td>42.0</td>
</tr>
<tr>
<td>Ambon</td>
<td>−3.70</td>
<td>128.08</td>
<td>12</td>
<td>Meisei manual</td>
<td>3 Apr 1992–11 Apr 1999</td>
<td>20.9</td>
</tr>
</tbody>
</table>

¹Ujung Pandang has been re-named as Makassar (an old name) in 1999. ¹¹Rawinsonde system is based on information in April 1997 information in April 1997. After that, some stations have changed their systems.
data by a low-pass filter with cut off period of 90 days.

Finally, the low-pass filtered pentad-mean data have been averaged for the eight years at each pentad number, at each standard pressure level and at each station. The results obtained after this procedure are regarded as the mean seasonal (73 pentads) data sets.

### 2.2 Supplement and comparison with GTS data

Rawinsonde data collected by NCEP through GTS (hereafter we call them GTS data) in an area of 15°S–15°N and 90°–140°E from 1992 to 1997 are also used in order to supplement and examine the BMG data. There are 142 stations in total (listed in the NCEP archive) in the area. We have checked the data availability at each station and have selected 33 stations (including the eleven BMG stations) as listed in Table 2 and also indicated in Fig. 1, at which wind data were obtained at 00 UTC on more than 657 days (30%) for the whole period (1992–97, 2192 days). The procedures mentioned in Subsection 2.1 are applied to make data sets. However, if the data were obtained twice a day (at 00 and 12 UTC), both the data have been used for the calculation.

### Table 2. Rawinsonde stations over South-East Asia (15°S–15°N, 90°–140°E) at which data were collected by NCEP. Data rate is the percentage of days on which data were obtained at any standard pressure levels during 1 Jan 1992–31 Dec 1997 (2192 days).

<table>
<thead>
<tr>
<th>WMO No. (Station)</th>
<th>Lat. (°N)</th>
<th>Long. (°E)</th>
<th>Elv. (m)</th>
<th>Period</th>
<th>Data rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>96035 (Medan)</td>
<td>3.57</td>
<td>98.68</td>
<td>25</td>
<td>1 Jan 1992–30 Dec 1997</td>
<td>73.8</td>
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<tr>
<td>96163 (Padang)</td>
<td>-0.88</td>
<td>100.35</td>
<td>3</td>
<td>1 Jan 1992–16 Dec 1997</td>
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<tr>
<td>96237 (Pangkal Pinang)</td>
<td>-2.17</td>
<td>106.13</td>
<td>33</td>
<td>2 Jan 1992–16 Dec 1997</td>
<td>67.3</td>
</tr>
<tr>
<td>96749 (Jakarta)</td>
<td>-6.12</td>
<td>106.65</td>
<td>8</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>62.4</td>
</tr>
<tr>
<td>96935 (Surabaya)</td>
<td>-7.37</td>
<td>112.77</td>
<td>3</td>
<td>2 Jan 1992–31 Dec 1997</td>
<td>81.9</td>
</tr>
<tr>
<td>97014 (Menado)</td>
<td>1.53</td>
<td>124.92</td>
<td>80</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>74.6</td>
</tr>
<tr>
<td>97072 (Palu)</td>
<td>-0.68</td>
<td>119.73</td>
<td>6</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>72.2</td>
</tr>
<tr>
<td>97180 (Ujung Pandang)</td>
<td>5.07</td>
<td>119.55</td>
<td>14</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>78.2</td>
</tr>
<tr>
<td>97372 (Kupang)</td>
<td>-10.17</td>
<td>123.67</td>
<td>108</td>
<td>2 Jan 1992–31 Dec 1997</td>
<td>62.8</td>
</tr>
<tr>
<td>97650 (Biak)</td>
<td>-1.18</td>
<td>136.12</td>
<td>11</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>43.4</td>
</tr>
<tr>
<td>97724 (Ambon)</td>
<td>-3.70</td>
<td>128.08</td>
<td>12</td>
<td>1 Jan 1992–6 Jun 1997</td>
<td>31.9</td>
</tr>
<tr>
<td>45333 (Port Blair)</td>
<td>11.67</td>
<td>92.72</td>
<td>79</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>79.7</td>
</tr>
<tr>
<td>48455 (Bangkok)</td>
<td>13.73</td>
<td>100.50</td>
<td>16</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>98.2</td>
</tr>
<tr>
<td>48565 (Phuket)</td>
<td>8.10</td>
<td>98.30</td>
<td>3</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>71.0</td>
</tr>
<tr>
<td>48568 (Songkhla)</td>
<td>7.20</td>
<td>100.60</td>
<td>4</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>89.6</td>
</tr>
<tr>
<td>48601 (Penang)</td>
<td>5.30</td>
<td>100.27</td>
<td>3</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>97.7</td>
</tr>
<tr>
<td>48615 (Kota Bharu)</td>
<td>6.17</td>
<td>102.28</td>
<td>5</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>96.3</td>
</tr>
<tr>
<td>48648 (Petaling Jaya)</td>
<td>3.10</td>
<td>101.65</td>
<td>57</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>98.2</td>
</tr>
<tr>
<td>48657 (Kuantan)</td>
<td>3.78</td>
<td>103.22</td>
<td>18</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>97.7</td>
</tr>
<tr>
<td>48698 (Singapore)</td>
<td>1.37</td>
<td>103.98</td>
<td>3</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>97.7</td>
</tr>
<tr>
<td>48900 (Saigon)</td>
<td>10.82</td>
<td>106.67</td>
<td>6</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>82.3</td>
</tr>
<tr>
<td>91408 (Koror)</td>
<td>7.33</td>
<td>134.48</td>
<td>30</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>96.1</td>
</tr>
<tr>
<td>91413 (Yap)</td>
<td>9.48</td>
<td>138.08</td>
<td>14</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>99.2</td>
</tr>
<tr>
<td>91420 (Darwin)</td>
<td>-12.43</td>
<td>130.87</td>
<td>29</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>99.7</td>
</tr>
<tr>
<td>91450 (Gove)</td>
<td>-12.27</td>
<td>136.82</td>
<td>54</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>97.7</td>
</tr>
<tr>
<td>96315 (Brunei Airport)</td>
<td>4.93</td>
<td>114.90</td>
<td>15</td>
<td>2 Jan 1992–31 Dec 1997</td>
<td>91.5</td>
</tr>
<tr>
<td>96413 (Kuching)</td>
<td>1.48</td>
<td>110.33</td>
<td>26</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>97.4</td>
</tr>
<tr>
<td>96441 (Bintulu)</td>
<td>3.20</td>
<td>113.03</td>
<td>5</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>93.6</td>
</tr>
<tr>
<td>96471 (Kota-Kinabalu)</td>
<td>5.95</td>
<td>116.05</td>
<td>3</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>96.4</td>
</tr>
<tr>
<td>96481 (Tawau)</td>
<td>4.27</td>
<td>117.87</td>
<td>20</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>92.5</td>
</tr>
<tr>
<td>96996 (Cocos Island)</td>
<td>-12.18</td>
<td>96.83</td>
<td>5</td>
<td>1 Jan 1992–31 Dec 1997</td>
<td>95.8</td>
</tr>
<tr>
<td>98444 (Legaspi)</td>
<td>13.13</td>
<td>123.73</td>
<td>17</td>
<td>1 Jan 1992–17 Feb 1997</td>
<td>29.2</td>
</tr>
<tr>
<td>98646 (Mactan)</td>
<td>10.30</td>
<td>123.97</td>
<td>26</td>
<td>8 Nov 1992–29 Nov 1997</td>
<td>36.4</td>
</tr>
</tbody>
</table>
The BMG station data included in the GTS data are not exactly the same as BMG data collected by ourselves directly, as mentioned in the previous subsection. First, the number of GTS data is more than that of the BMG data collected directly (compare the data rate of Tables 1 and 2). Second, the GTS data include apparently more erroneous data than the BMG data. Figure 2 shows comparison between the BMG and GTS data for wind speed and direction at Surabaya station. The data are plotted only when both the BMG and GTS data we obtained simultaneously at a standard pressure level. For wind direction (Fig. 2(a)), a number of the GTS data are 0 in spite of the fact that BMG data have a non-zero value. Some of GTS wind speed data (Fig. 2(b)) are also 0 and others are sometimes apparently erroneous (e.g., greater than 100 m/s). Furthermore, there are some data slightly different from each other, which may be due to problems in real-time analysis for sending data through GTS within limited time, manpower and calculation tool. Therefore, for the stations in the Indonesian territory, we use BMG data collected directly rather than the GTS data.

In addition, the NCEP reanalysis data is also used in order for comparison with the rawinsonde data and calculate a longitudinal (90°–140°E) mean wind field. Data at 00 UTC during 1992–97, and the climatological monthly mean data (1979–95) at pressure levels from 1000 to 50 hPa are used. These were originally provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA.

2.3 Comparison and reliability check with BLR data

Since November 1992, three-dimensional winds in the lower troposphere (below 6.4 km altitude) have been observed continuously with vertical and temporal resolutions of ~100 m and ~1 min, respectively, using a 1.3-GHz wind profiler, called boundary layer radar (BLR) at Serpong (6.4°S, 106.7°E), near Jakarta, West Jawa, Indonesia (Hashiguchi et al. 1995a). Comparisons have been made between the BLR data at 1.5, 3.0 and 5.5 km altitudes and the rawinsonde data at 850, 700 and 500 hPa at BMG Jakarta station which is located about 0.3° (30 km) north of the BLR site. For the BLR data, a one hour mean throughout the analysis period was taken. In order to filter out local and shorter variations, pentad-mean for both data has been made applying the same procedure as mentioned in Subsection 2.1.

Figure 3 shows time variations of pentad-mean zonal and meridional wind for both data. Wind directions agree well with each other throughout the observational period, but the
wind speed of the BMG rawinsonde data seems to be 2–3 m/s larger than that of BLR. This may be caused by a fact that the BMG Jakarta rawinsonde station is located near the seacoast, whereas the BLR site is inland (wind speed at Serpong is suppressed by friction with land). There are no problems with the reliabilities of both observation data.

3. Seasonal-vertical variations at each station

Seasonal-vertical variations of zonal and meridional wind components are analyzed for all 33 stations listed in Table 2, after the eight- (for BMG data) or six- (for GTS data) year mean, low-pass filtered and pentad-mean procedures described in the previous section. However, we focus into results only for the 11 stations in the territory of Indonesia listed in Table 1.

3.1 Zonal wind

Figure 4 shows seasonal-vertical variations of zonal wind at each rawinsonde station. All the results show that easterly is dominant in the upper troposphere above 8 km, and not so in the lower troposphere. The tropical trade wind near the surface is not dominant throughout the year, which has been considered mainly due to a superposition of seasonally reversing monsoon circulation. Several earlier studies (e.g., Chang and Krishnamurti 1987) have shown such features, but their major characteristics are summarized in order to discuss more detailed structures of wind variations, in the remainder of this paper.

a. Classification into three latitudinal regions in the lower troposphere

Based on the features of zonal wind variations in the lower troposphere (below about 8 km), Indonesia and its surroundings are classified into three regions as will be mentioned below. First, we have sorted out stations which have westerly wind for less than 48 pentads (not more than two-thirds of one year) in the mean seasonal data sets. Next, these stations are classified based on whether the westerly maximum appeared at pentad numbers 42–49 (July–September) or at 71–11 (December–February), which are defined by Region I or II, respectively. The remainder (stations at which westerly wind appears for more than 48 pentads) was classified into Region III. All 33 stations were classified into these three regions, except for Manado and Cocos. Manado has westerly wind in February–March and in September–December in the mean seasonal variations (less than 48 pentads), but this station is classified in Region III, because westerly wind appears often throughout a year. Cocos island has a weak westerly maximum at pentad 31 (early in June) at 500 hPa, but this station was categorized in Region II because the westerly maximum is continued from the upper troposphere, (and the variation in the lower troposphere is very similar to that in Region II). In an earlier study, Matsumoto (1992) divided the Indonesian region into three climatological regions, based on ECMWF (European Center for Medium Range Weather Forecasts) objective analysis data. His A-1 (westerly dominant) and A-2 (easterly dominant) regions correspond to our Region III, and his B-1 regions in the northern and southern hemispheres correspond to our Regions I and II, respectively.
Fig. 4. Seasonal-vertical variations of zonal wind observed by BMG rawinsondes. All period (November 1991–May 1999) averaged pentad (5-day) mean values are plotted. Period components shorter than 90 days have been removed by a low-pass filter. See text for details.
The climatological classification mentioned above is indicated in Fig. 1. Region I is mainly in the northern hemisphere. This region has a clear annual oscillation with westerly (easterly) during northern summer (winter). Westerly becomes stronger with increasing latitude, and exceeds 6 m/s in the northern side of 7°N in the Malay Peninsula (see, Bangkok in Fig. 4). The phase (appearance date of positive peak) has a longitudinal dependence, with about 1 month delay for about 30°. The westerly maximum appears in July–August near 100°E (Indochina and Malay Peninsula; see Bangkok and Kota Bhalu in Fig. 4) and August–September near 130°E (Koror, shown in Fig. 4, and Yap Islands).

Region II is in the southern hemisphere. This region has an annual oscillation with inverse phases against Region I; westerly (easterly) wind appears during northern winter (summer). These two regions have symmetric geographical features about the equator: westerly wind becomes stronger with increasing latitude, and the maximum appearance has an eastward delay from December–January near 100°E (Pangkal Pinang) to February near 130°E (Ambon). At the most southern stations (Kupang, Cocos Island, Darwin and Gove; see Darwin in Fig. 4), the length of westerly period is shorter than that at northern stations in Region I, but wind magnitudes of easterlies in the residence season are very strong.

Region III is in the vicinity of the equator. Zonal winds are weaker than 3 m/s throughout a year, and their seasonal variations are quite unclear. Looking more carefully, the center of Region III (~1°S–~4°N) is not just at the equator, but slightly shifted to the northern hemisphere.

b. Upper troposphere

In the upper troposphere, the easterly jet stream exists and has two maxima in January–February and in July–August, that is, a semiannual oscillation appears at almost all the stations. The amplitude of this semiannual oscillation is largest near the equator (Region III). Each winter easterly maximum (January–February in Region I and July–August in Region II) is generally weaker than the summer maximum, and such a winter-summer difference becomes clearer with increasing latitude. The easterly finally turns to westerly at stations located north of 10°N in Region I (see Bangkok in Fig. 4), and also at stations in Australia (~12°S, see Darwin in Fig. 4) in Region II, so that the annual oscillation becomes gradually dominant toward each mid-latitude. Appearance of the summer maximum in each hemisphere has a longitudinal dependence, being in good agreement with that of the westerly in the lower troposphere mentioned in the previous subsection. On the other hand, the winter maximum has no systematic longitudinal dependence.

3.2 Meridional wind

Figure 5 shows seasonal variations of meridional wind at the same stations as in Fig. 4. An annual oscillation with southerly (northerly) during northern winter (summer) is observed in the upper troposphere at all 33 stations analyzed in this study, and weaker inverse one in the lower troposphere. The boundary altitude of these seasonal variations anti-phased with each other is about 8 km, which looks very close to the boundary between annual (lower troposphere) and semiannual (upper troposphere) variations of zonal wind mentioned in the previous subsection. The vertical and seasonal reversals of meridional wind observed here are not strange, if we imagine that twin cells similar to the Hadley circulation exist and ITCZ (inter-tropical convergence zone) as the boundary of the cells moves with seasons. These will be considered and discussed in detail in the subsequent sections. Here, we look at the observational evidence more precisely.

In Region I, the annual oscillations of meridional wind are clear. Southerly winds during northern winter in the upper troposphere exceed 6 m/s except for Medan, and are comparable to, or 1–3 m/s larger than, northerly winds during northern summer. The southerly-wind period tends to lengthen northward; about five months (from end of November to mid-April) at Burunei (~4°N), and about seven months (from mid-October to early May) at Bangkok (~14°N), at 14 km altitude. In the lower tropo-

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4 If we take a deviation from annual mean (figures are not shown), Port Blair has somewhat different feature from this description, but all the other stations have results similar to features mentioned in the text.
Fig. 5. Same as Fig. 4, but for meridional wind.
sphere, the phase is reversed from that in the upper troposphere at most stations, but southerly at Bangkok appears during March–May, which is not in contrast with northerly in the upper troposphere (June–August).

In Regions II and III, southerly winds in the upper troposphere are weaker, and the annual oscillation becomes unclear southward. At Jakarta, northerly (southerly) wind is dominant throughout the year in the upper (lower) troposphere. At southeastern 4 stations in Region II (Ambon, Kupang, Darwin and Gove), meridional wind variations in the upper troposphere show semiannual periodicity.

In all Regions, the appearance period of the meridional wind maxima in the lower and upper troposphere has a longitudinal dependence which is consist with those of easterly (upper troposphere) and westerly (lower troposphere) in zonal wind described in the previous subsection.

4. Meridional cross-sections in the Indonesian sector

To reveal the meridional structure of seasonal variations described in the previous section more clearly, latitude-altitude cross-section analysis has been made for monthly averaged zonal and meridional wind components, as shown in Figs. 6 and 7, respectively. All the 33 stations have been used. It must be noted that the stations plotted here are not along a longitude.

For zonal winds (Fig. 6), an easterly region appears in the upper troposphere over the equatorial region throughout a year. In summer seasons of each hemisphere (December–February and July–September), the easterly wind becomes strong, and is distributed continuously from the summer hemispheric stratosphere. This easterly wind region is accompanied by westerly in the lower troposphere and is shifted north-southward with an annual period. When centers of these regions come to the equator (in April and November), zonal winds, both in the upper and lower troposphere, become relatively weak. Namely, the weak annual cycle in Region III (~1°S~4°N) in the lower troposphere (Subsection 3.1a) are easily confirmed here, and the strength of the upper-tropospheric easterly over the equatorial region takes maxima in each summer season and minima between them, corresponding to the semiannual oscillation described in Subsection 3.1b.

The meridional winds in the upper troposphere over the equatorial region are reversed at around 8 km altitude moving in the north-south direction with an annual cycle (see Fig. 7) as found in Subsection 3.2, which is consistent with the annual-cycle displacement of the twin meridional (Hadley-type) cells. The reversal latitude corresponding to ITCZ or the boundary of the twin meridional cells (defined zero line in the meridional wind) arrives at the southernmost latitude (about 15°S) in February and at the northern limit (outside of the analysis region limit ~15°N) from May to September, that is, the displacement from the equator is asymmetric between both hemispheres (or both summer seasons). The seasonal march (or northward movement of the meridional cell boundary is the most rapid from April (the cell boundary locating over the equator) to May in the analyzed longitude range (90°–140°E).

The description mentioned above is averaged under an assumption that the atmosphere is almost uniform for the longitudinal range analyzed here (90°–140°), the meridional circulation is not uniform even inside Indonesia considering longitudinal dependences of seasonal variation of zonal and meridional wind described in Subsection 3.1 and 3.2. Murakami and Matsumoto (1994) have shown the differences of the north-southward migration of ITCZ (that is, the Hadley-type cell boundary) inside and around the maritime continent region (80°–140°E) based on the NOAA OLR (outgoing long-wave radiation) data. The latitude (~10°S) of ITCZ during December–March in their analysis is consistent with that of the meridional (Hadley-type) cell boundary defined by zero meridional wind, shown in Fig. 7 of this paper. ITCZ reaches the most northern latitude in July–August at 100°E, and in August–September at 140°E. This longitudinal dependence is consistent with that of the appearance of the westerly (easterly) and southerly (northerly) maximum in the lower (upper) troposphere, as described in Subsection 3.1 and 3.2. (Murakami and Matsumoto (1994) has also pointed out a ‘sudden’ shift of ITCZ in the Indonesian sector described in the previous paragraph.) Therefore, the north-south ward
Fig. 6. Latitude-altitude cross-sections of monthly averaged zonal wind obtained by hypothetically arranging all the stations along a common longitude.
Fig. 7. Same as Fig. 6, but for meridional wind.
migration of meridional circulation is different between the western and eastern parts of Indonesia.

5. Comparison with NCEP reanalysis data

Figure 8 shows the difference of zonal wind between the NCEP reanalysis at each nearest grid point and the BMG data (shown in Fig. 4). NCEP reanalysis data used here is only 00 UTC in 6-hourly data during 1992–1997, and procedures in making datasets are the same with that in operational rawinsonde data. A positive value suggests a positive (westerly) bias in the NCEP objective analysis. The dif-

Fig. 8. Contour plot of difference between the operational rawinsonde data and NCEP reanalysis data, in mean seasonal variation for zonal wind. Values subtracted operational rawinsonde data from NCEP reanalysis data are plotted in each pentad.
ferences seem to be large near the bottom and top of the troposphere, but have no clear systematic distributions almost over the Indonesian stations, which implies that the seasonal-vertical variations of wind calculated by the NCEP objective analysis are in good agreement with actual variations. In the upper troposphere, easterly maximum in January–February is underestimated in Ujung Pandang. Except for this, the upper troposphere has in general negative values in Fig. 8, which implies that the NCEP objective analysis involves a negative (easterly) bias, and produces an overestimation of tropical tropopausal easterly. A maximum value in July–August is overestimated by 5–6 m/s, especially at stations in Region III (Medan, Padang and Manado).

Figure 9 is the same as Fig. 8, but for meridional wind. The differences seem again to be large near the top and bottom of the troposphere. In particular, northerly in the upper troposphere in northern summer is stronger (overestimated) in the NCEP reanalysis than the observations at all the Indonesian stations. The appearance altitude of maximum has good agreement, northerly wind changed steeply in altitude in the NCEP reanalysis data (showing positive (underestimated) regions in the upper and lower sides of the northerly maximum). Southerly wind in northern winter analyzed by NCEP is also stronger than from observations at four western stations (Medan, Padang, Pangkal Pinang and Jakarta).

Next, latitude-altitude cross-sections are compared between observations Fig. 7 and monthly-mean NCEP reanalysis data during 1992–1997 averaged for 90–140°E (Fig. 10). Concerning the southward shift of the boundary of twin meridional (Hadley-type) cells in northern winter, southerly wind larger than 6 m/s is beyond the equator in February in the observations, but until 4°N in the NCEP reanalysis. Strong northerly wind (larger than 6 m/s) in NCEP appears in a broader latitude range in the northern summer upper troposphere, and is continued longer until September. In the BMG rawinsonde data, the region of northerly wind larger than 6 m/s has a latitudinal dependence inside of 15°S–15°N (mainly 0–8°N in August). Surface wind is weaker in Fig. 10 than in observations. This difference appears with increasing latitude in both hemispheres in northern summer (July–September), and only in the northern hemisphere in northern winter (December and January). Although we have also compared between the GTS wind data (shown in Section 3) and NCEP reanalysis wind data, differences are smaller (1–2 m/s) than those between the BMG data and the NCEP reanalysis (Figures are not shown).

6. Discussions

6.1 Behaviors of meridional and zonal circulations

Figure 11 shows a schematic picture of observational evidence described in Sections 3 and 4. Existence of two types of circulation has been suggested over Indonesia and the surrounding region from the operational rawinsonde data; one is a pair of meridional (Hadley-type) circulation cells in a meridional-vertical plane, and the other is a zonal (Walker-type) circulation in a zonal-vertical plane. The annual oscillation of meridional wind observed at each station (Fig. 5) is mainly due to north-south shift of the meridional circulation. The winter (southern) hemispheric cell during the northern summer shifts deeper than that (northern cell) during northern winter. However, meridional wind over Indonesia associated with the winter hemispheric cell during northern winter is stronger than that during northern summer (Fig. 7 from the BMG and GTS rawinsonde data, and Fig. 10 from the NCEP reanalysis). These features also appeared in the zonal-mean Hadley circulation shown by Oort and Yienger (1996) and Waliser et al. (1999) using mass stream functions. Meridional wind with the winter-hemispheric cell of the meridional circulation in the Indonesian sector or 90°–140°E is stronger, and its invasion into the summer hemisphere is deeper than in the zonal-mean Hadley-circulation. Such strongly asymmetrical structure and displacement of the meridional cells make the latitudinal (regional) differences of the annual oscillations in the rawinsonde data. In Region I (mainly northern hemispheric stations), the central part of winter hemispheric cell comes in each solstice season, and the annual oscillation is quite clear. In Region II (mainly southern hemispheric stations), beyond which the boundary of the twin meridional cells does not pass through southward
even in southern summer, seasonal variations are relatively unclear, and northerly is dominant throughout the year.

Zonal circulation with westerly (easterly) in the lower (upper) troposphere over the Indonesian region (see, e.g. Holton 1992, Subsection 11.1.5) is also considered to migrate north-southward with ITCZ and meridional circulation, and this annual migration may produce annual variations of upper easterly and lower westerly in the troposphere (at least partly). The center (upwelling) of zonal circulation is located in the meridional cell boundary (or ITCZ) to the east of the analysis region. Therefore, as shown in Figs. 4 and 6, westerly in the lower troposphere is dominant in the summer
Fig. 10. Same as Fig. 7, but for meridional wind averaged for 90–140°E based on the NCEP re-analysis (1979–1997).
hemisphere over Indonesia (Regions I and II), and the period of dominance becomes shorter with latitude. Similar variations with different phases have been observed in zonal wind over the equatorial Pacific (Gage et al. 1996). In Indonesia studied here, associated with the meridional cell boundary and ITCZ, the westerly dominant zone is deviated to the northern hemisphere, and annual wind variation in Region III (Medan, Padang, Singapore, Bintulu, Kuching and Manado) is unclear, or westerly dominant throughout a year. However, this explanation cannot give the origin of the semianual oscillation of zonal wind which is more dominant than the annual oscillation in the upper troposphere over Indonesia.

In order to consider why semiannual variations are dominant in the upper-tropospheric easterly, a simple situation such as an air parcel starting from the top (near the tropopause) of the meridional circulation cell boundary is flown to the equator with the top of the winter-hemispheric meridional circulation cell. As shown in Section 3.1, the upper tropospheric easterly has a maximum more than 20 m/s in each solstice season, and becomes ~10 m/s in
other seasons. It takes about three days for an air parcel to go across the analysis region from east to west (∼5000 km) with 20 m/s, and takes six days with 10 m/s. On the other hand, as shown in Sections 3.2 and 4, upper tropospheric meridional wind speed is ∼6 m/s, so an air parcel can cross over the analysis region north-southward (∼3000 km) in six days. Because the distance between the meridional circulation cell boundary and the equator is shorter than half of the north-south width of the analysis region (except for northern summer), it takes less than three days for a parcel to travel from the cell boundary to the equator with the winter-poleward flow at the top of the winter hemispheric cell; in other words, an air parcel moving with the meridional circulation can remain in the analysis region (does not go to western outside of the analysis region), and a one-dimensional (meridional) problem of the conservation of absolute angular momentum can be approximately applied

$$\Omega \cdot (a \cos \varphi)^2 + u(\varphi) \cdot a \cos \varphi = \Omega \cdot a^2 + u(0) \cdot a,$$

(1)

to the air parcel transported from a latitude $\varphi$ to the equator ($\varphi = 0$), where $u(\varphi)$ is the zonal wind at latitude $\varphi$, $\Omega$ is the angular velocity of the earth’s rotation, and $a$ is the earth’s radius (see, e.g. Holton 1992, Section 10.3, pp. 323–329).

If the boundary of the meridional circulation cells is shifted from the equator and is located at $\varphi = \varphi_H$, the zonal velocity of this air parcel at the equator is given by (1) as

$$u(0) = u(\varphi_H) \cdot \cos \varphi_H + \Omega \cdot a \cdot (\cos^2 \varphi_H - 1),$$

(2)

where $u(\varphi_H)$ has been assumed as an almost constant (small negative) value, because the equatorial lower atmosphere (the momentum source) is sufficiently homogeneous within the latitudinal range $0 < |\varphi| < |\varphi_H|$. Thus, $u(0)$ becomes minimum when the north-south shift $|\varphi_H|$ of the meridional circulation cell boundary is maximum.

Furthermore, because the southward shift of the meridional circulation cell boundary $|\varphi_H|$ in northern winter is smaller than the northward shift in summer, the easterly maximum in northern winter becomes weaker than that in summer. Therefore, a weak annual variation is generated. Combined with the discussion in the previous paragraph, the seasonal variation of zonal wind over the Indonesian region is related to the effect of meridional (Hadley-type) circulation mentioned above (strong semi-annual plus weak annual) and the superposition of zonal (Walker-type) circulation (mainly annual), as long as the zonal displacement is not so long as to go out of the analyzed region. Contribution of the former is relatively large in the vicinity of the equator, and the latter is dominant in particular over the summer hemisphere-side relatively higher latitudes (near ITCZ), as shown in Fig. 6. This consideration is also consistent in quality with the observational fact that easterly maximum in winter of each hemisphere becomes stronger than the other maximum (in winter of each hemisphere) and annual oscillation becomes gradually dominant with increasing latitude, as shown in Subsection 3.1.b and Section 4.

Other effects such as eddy viscosity working on the zonal flow must be considered to explain the origin of the behaviors of the annually-oscillating meridional circulation accompanied with semi-annual variations of upper-tropospheric easterly. Monsoon circulation between the northern (land) and southern (ocean) hemispheres may induce flows in the same direction as the meridional (Hadley-type) cell (winter-poleward in the upper troposphere) in the winter hemisphere. However, quantitative discussions on such effects are beyond the scope of this paper.

### 6.2 Significance of operational rawinsonde data over Indonesia

In this subsection, based on comparison with NCEP reanalysis data shown in Section 5, the significance and utility of the operational rawinsonde data over Indonesia are discussed, many of which have not been included in such objective analysis mainly because of worse telecommunication infrastructure as described in Subsection 2.1.

Analysis results in this paper, based on the operational rawinsonde data, have revealed the existence of regional differences of large-scale circulations, even inside of the Indonesian sector. In general, differences in wind velocities seem to be larger near the top and bottom of the troposphere. As shown in Figs. 8 and 9,
maximum values of wind speed are different between the observations and the reanalysis, and seasonal alternation in the lower troposphere is inverse at a station. In the observations, the upper-tropospheric northerly wind in northern summer is weaker than southerly in northern winter and is larger than 6 m/s in a narrow latitude range (Figs. 4 and 7). However, in the NCEP reanalysis, the northerly wind in northern summer is over-estimated and has a magnitude similar to that of the southerly in northern winter. This suggests that the meridional circulation cells are not well reproduced in the NCEP reanalysis.

Furthermore, in the NCEP reanalysis, the northerly in northern summer is distributed broadly over the analyzed latitude range in both sides of the equator and the boundary of meridional circulation \((v = 0 \text{ line})\) in 200 hPa is extended to \(\sim 35^\circ\text{N}\). Although the rawinsonde stations used in this study (latitude \(< 15^\circ\) do not cover the cell boundary in northern summer, observations of ITCZ in the analysis longitude range \((90^\circ - 140^\circ\text{E})\) shows that it is located over the Bay of Bengal and Indo-China Peninsula \((\sim 20^\circ\text{N})\). This suggests that the northward invasion of the winter hemispheric meridional circulation cell across the equator is overestimated in the NCEP reanalysis. A similar feature has been suggested for winter hemispheric Hadley cell in northern summer analyzed from zonal mean of the NCEP reanalysis (Waliser et al. 1999). Overestimation of easterly maxima in July–August in the NCEP reanalysis may occur as a result of such errors (too large northward invasion) in the meridional circulation cells which are related to the absolute angular momentum conservation as discussed in the previous subsection.

### 7. Conclusions

Operational rawinsonde data from 11 stations over the whole territory of Indonesia for about seven years (November 1991–May 1999) has been collected. Rawinsonde data at stations in countries surrounding Indonesia for six years (1992–1997), and objective analysis data have been obtained from NCEP for comparison. BLR data near Jakarta also has been used for a reliability check. Based on these datasets, seasonal variations of general circulation over Indonesia have been investigated, and the variations have been compared with the NCEP reanalysis data. Major conclusions are summarized as follows:

(i) Meridional wind in the troposphere varies by an annual period associated with a north-south shift of meridional (Hadley-type) circulation. The summer-poleward shift of the twin meridional circulation cell boundary is larger in northern summer (southern winter), but the intensity of winter-hemispheric meridional cell is stronger during northern winter. The latter makes upper (lower) tropospheric southerly (northerly) in the northern winter stronger than each inverse flow in northern summer;

(ii) Annual oscillation of zonal wind is not so strong, but becomes clear with increasing latitude [westerly (strong easterly) in summer of each hemisphere in the lower (upper) troposphere]. A possible explanation is due to a north-south shift of zonal (Walker-type) circulation (westerly and easterly in the lower and upper troposphere, respectively, over Indonesia) superimposed along the boundary of twin meridional circulation cells;

(iii) Zonal wind in the upper troposphere varies more clearly by a semiannual period which has easterly maxima in both the solstice seasons. This is consistent with a consideration on the absolute angular momentum conservation of air parcels transported equatorward (winter-poleward) by the annually shifting twin meridional circulation cells (semiannually replacing winter-hemispheric cells). Differences between the two maxima (a kind of annual variation) are also induced by an asymmetry of annual variation of the meridional circulation; and,

(iv) Seasonal alternation of wind in NCEP reanalysis data are almost consistent with that in operational rawinsonde data. However, in magnitude of wind, overestimations of upper tropospheric northerly and easterly are seen in the NCEP reanalysis data, especially in northern summer. The overestimations may be associated with a worse reproduction of the winter (southern) hemispheric meridional circulation...
cell, such as too large invasion to the summer (northern) hemisphere across the equator.

We are continuing our efforts to collect observation data in Indonesia for a much longer period, in order to analyze interannual variations and investigate correlations with ENSO (El Niño-southern oscillation; cf. Hamada et al. 2002 for rainfall data) or other long-periodic variations, which will be presented in a subsequent paper. Furthermore, longitudinal differences of the tropical general circulation (the meridional and zonal circulations), which have been suggested even inside the Indonesian sector, will be studied also between Indonesia and other equatorial regions, and then latitudinal differences (tropics-extratropics interactions) will be studied in parallel with the interannual variation analysis.

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