学校编码：10384　　　　　　　　　　分类号____密级____
学号：22420110153621　　　　　　　　　　UDC____

厦门大学

博 士 学 位 论 文

南海和苏禄海的氟氯烃分布、通风过程及人为碳估算研究

Study on CFCs Distribution, Ventilation Processes and Anthropogenic CO_2 Estimates in the South China Sea and Sulu Sea

黄　鹏

指导教师姓名：陈立奇　研究员
　　　　　　　蔡明刚　教　授

专　业 名 称：海　洋　化　学
论文提交日期：2015 年 5 月
论文答辩时间：2015 年 5 月
学位授予日期：　　　年　　月

答辩委员会主席：李立　研究员
评　　阅　　人：____________

2016 年 9 月

厦门大学学位论文原创性声明

本人呈交的学位论文是本人在导师指导下,独立完成的研究成果。本人在论文写作中参考其他个人或集体已经发表的研究成果，均在文中以适当方式明确标明，并符合法律规范和《厦门大学研究生学术活动规范（试行）》。

另外，该学位论文为（　　　　　　　　　　　　　　）课题（组）的研究成果，获得（　　　　　　　　）课题（组）经费或实验室的资助，在（　　　　　　　）实验室完成。（请在以上括号内填写课题或课题组负责人或实验室名称，未有此项声明内容的，可以不作特别声明。）

声明人（签名）：

年　　月　　日

厦门大学学位论文著作权使用声明

本人同意厦门大学根据《中华人民共和国学位条例暂行实施办法》等规定保留和使用此学位论文，并向主管部门或其指定机构送交学位论文（包括纸质版和电子版），允许学位论文进入厦门大学图书馆及其数据库被查阅、借阅。本人同意厦门大学将学位论文加入全国博士、硕士学位论文共建单位数据库进行检索，将学位论文的标题和摘要汇编出版，采用影印、缩印或者其它方式合理复制学位论文。

本学位论文属于：

（　　）1.经厦门大学保密委员会审查核定的保密学位论文，于　　年　月　日解密，解密后适用上述授权。

（　　）2.不保密，适用上述授权。

（请在以上相应括号内打“√”或填上相应内容。保密学位论文应是已经厦门大学保密委员会审定过的学位论文，未经厦门大学保密委员会审定的学位论文均为公开学位论文。此声明栏不填写的，默认为公开学位论文，均适用上述授权。）

声明人（签名）：

年　月　日

目录

CONTENT

摘要

本研究以 CFCs、SF_6 数据为基础，基于 TTD 方法开展南海、苏禄海上层水体的通风过程及时间尺度研究，以 TTD 方法计算南海、苏禄海人为碳含量，进而估算整个研究海域的人为碳储量，并采用一维平流扩散模式和瞬时稳态理论探讨研究海域的垂直扩散率和上升速率。

南海 1500 m 以深的水体 CFC-11 含量极低，2000 m 以深的水体源于邻近的西太平洋的不含 CFC-11 的深层水体的输入。苏禄海的 CFCs 渗透深度大于南海，主要来源于临近海域水体的输入。

南海表层 0-150 m 的水体的平均年龄为 0-30 年，通风时间较短。500 m 的平均年龄约 170 年，明显大于上层水体。500-1500 m 的水体平均年龄随着深度增加从 170 年增大到超过 400 年。而深度大于 1500 m 的水体，平均年龄超过 500 年。500-1500 m 的水体表现出了显著的平均年龄的差异，存在从北到南“老化”的特性，南部水体平均年龄比北部增加了约 80 年。这一南北的平均年龄差异表明，南海南部中深层水体的通风时间大于北部，表明南海存在深层的翻转流系统。而苏禄海 400 m 以深水体的平均年龄要明显小于南海，两者的差异约为 100 年，苏禄海和南海的深层水体的通风时间有明显的差别。表明苏禄海深层水来源于周围海盆次表层水体的输入。

南海人为碳的渗透深度约 1500 m，与 CFCs 的分布是吻合的。人为碳分布也表现出南北的差异，500 m 以深水体中的人为碳含量北部高于南部。苏禄海人为碳也表现出随深度增加递减的趋势，不过其渗透深度约 2500 m，显著大于南海，这主要源于周围海盆的人为碳的信号的输入。

2011 年南海的人为碳储量为 1 Pg（误差范围：0.8-1.3 Pg），单位面积储量为 24 mol· m^{-2}。苏禄海在 2011 年人为碳储量为 100 Tg（误差范围：78-128 Tg），单位面积储量为 24 mol·m^{-2}。南海和苏禄海的人为碳储存能力相仿，不过相较太平洋而言，其储存人为碳的能力较低，主要原因在于南海、苏禄海没有深层水生成的机制，人为碳信号无法大量进入深层水体。通过与反算法得到的结果进行比较，两种方法在南海的结果是吻合的，不过反算法高估了苏禄海的人为碳数值。

南海 500 m 以深的水体上升速率为 13-34 m yr^{-1}，明显高于北太平洋深层水体的水平。基于该上升速率估算的南海 500 m 以深水体停留时间约为 60-140 年。南海 500 m 以深的垂直扩散率为 2-4.6×10^{-4} m^2 s^{-1}，明显高于开阔大洋。苏禄海的扩散率为 1.1×10^{-4} m^2 s^{-1}。南海与苏禄海的较大的垂直扩散率主要源自内部强烈的内波造成的。

关键词：瞬态示踪物；运移时间分布；人为碳；通风；南海；苏禄海

ABSTRACT

The CFC-11, CFC-12 and SF_6 measurements present here together with the application of the TTD method provide new data of mean ages and C_{ant} concentrations in the South China Sea (SCS) and the Sulu Sea (SS).

For the SCS, The CFC-11 concentration decrease rapidly with depth and close to the detection limit below about 1500 m, indicating there is no deep or bottom water formation in the SCS. The mean ages increase rapidly with the depth and increase to the value exceed 500 years at the ~1500 m in the northern SCS and ~1000 m in the southern SCS, respectively. The intermediate water in the southern part is approximately 100 years older than the northern part, suggesting the existence of mean annual cyclonic circulation in the SCS. The C_{ant} decrease exponentially with depth and has penetrated to the depth of ~1 500 m, where the concentration of C_{ant} <5 μmol kg^{-1}. The mean column inventory in the north SCS (i.e. line along the 18°N) is 28.9 mol m^{-2} (error range (ER): 22.8-35.6 mol m^{-2}), while the south SCS (i.e. stations south of 13°N) is 28.4 mol m^{-2} (ER: 21.9-35.2 mol m^{-2}). The regional difference of column of C_{ant} in the SCS is in agreement with the CFC-11 data. The value of column inventories in the SCS, however are the small values compared to those estimated for the remainder of the world ocean with the TTD method. The total inventory of C_{ant} in the SCS is 1 Pg (ER: 0.8-1.3 Pg). It is not surprising that SCS stores less C_{ant} compared to other marginal sea due to the absence of overturning circulation systems and plays a minor role in transporting C_{ant} to the interior North Pacific.

For the SS, The transient tracer CFC-12 was found throughout the entire water column in the SS, but at concentration below 10 ppt in the deep SS below about 2500 m. The penetration depth of CFCs in the SS is deeper than in the SCS, which means the deep SS may be ventilated from the subsurface water of SCS or Celebes Sea. The mean ages increase with depth monotonically and exceed 400 years below the 2500 m, where the concentrations of CFC-12 are close to the analytical detection limit and have large uncertainty. But the mean ages in the SS deeper than about 400 m are shorter (the CFC-12 concentrations are higher) than the SCS, indicating the relatively shorter ventilation time in the SS compared to the SCS.

The results presented here show that the substantial amount of C_{ant} has penetrated to the depth of about 2500 m. The Cant concentrations are lower than 5 μmol kg^{-1} in the deep and bottom layers deeper than ~2500 m. The mean column inventories of 42.3 mol m^{-2} (ER: 32.4-54.2 mol m^{-2}) are moderate compare to those in the surrounding seas and Pacific Ocean. The total C_{ant} inventory of the SS is estimated to 100 Tg (ER: 78-128 Tg), although this is probably an overestimate of 15-20% stemming from the assumption of time invariant disequilibrium of CO_2. It is also found that our result of C_{ant} estimates is significant smaller than the result of Chen et al. (2006) who report on concentration in the deep water column greater than ~20 μmol kg^{-1} based on different assumptions of mixing and ventilation timescales and on a different C_{ant} calculation technique. We suggest that the result from TTD method is more realistic in the SS. Based on the "transient steady state" concept and approximate method we estimate the vertical diffusivity for the SS K_z of 1.1×10^{-4} m^2 s^{-1}. The result shows that the SS has the significant vertical diffusivity, like the SCS, is more or less due to the strong internal waves and the series of solitary waves.

We have successfully applied the TTD method to the SCS and SS but had only access to one independent transient tracer and hence an empirical constraint on the shape of the TTD could not be carried out. In order to constrain the TTD, simultaneous measurement of CFCs and other transient tracers, such as SF_6, ^3H, ^{14}C or ^{39}Ar (the latter two can resolve the longer time scales of the deep water ventilation) would be useful for constraining ventilation of the SCS and SS better. More repeat data should be obtained to understand more about the long term trend of ventilation times and C_{ant} storage not only in the SCS and SS but also in the adjacent Celebes Sea (CS) in order to understand more about the ventilation timescale and long term C_{ant} storage in these areas. The data could put an important constraint to the modeling. Meanwhile, more accuracy model should be used to simulate the SCS and SS flow