

南海北部跨陆坡运动的模式诊断分析

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摘要 基于POM诊断模型, 用GDEM气候态温盐资料, 对南海环流进行诊断计算. 结果表明, 南海北部普遍存在跨陆坡运动且具有明显空间分布特征. 从水平和垂直断面分布可知, 较强的跨陆坡运动发生于浅水陆坡和海底地形急剧变化的海区. 跨陆坡运动引起近岸陆架与外洋之间的水交换, 其输运量估算为: 沿200, 500和1000 m等深线断面的跨陆坡体积输运年平均值分别为9.4, 15.8, -2.1 Sv, 热含量输运的年平均值分别为0.78, 0.84, -0.22 PW, 盐含量输运的年平均值分别为342.5, 575.0, -76.0 Gg s⁻¹. 这3处断面之间水体产生辐聚或辐散, 造成显著的跨陆坡输运. 跨陆坡运动同时伴随着热盐输运, 即有大量的热量和盐分向陆架海区输送, 而少量向外洋输送, 且沿200和500 m等深线断面的跨陆坡输运存在冬强夏弱的季节差异. 200~500 m等深线之间的海区主要为向陆架方向的跨陆坡输运, 而500~2000 m等深线之间的海区主要为向外洋方向的输运. 陆坡流中跨陆坡运动成分不可忽视, 占15%~20%. 正压涡度平衡方程逐项分析发现, 地形与斜压联合效应项、位势涡度平流项、对流和扩散项对跨陆坡运动起主要贡献. 地形与斜压的相互作用是跨陆坡运动产生的主要因素, 且在118°E以东区域对跨陆坡运动起显著的增强作用.

关键词 南海, 诊断模型, 跨陆坡运动, 输运, 涡度平衡

海洋中流速矢量沿地形梯度分解, 其中得到沿地形梯度方向的分量为跨陆坡分量, 本文称其为跨陆坡运动; 而垂直于地形梯度方向的分量为沿陆坡分量, 称其为沿陆坡运动. 跨陆坡运动引起水体跨越地形等深线向陆架或外洋方向输运, 从而引起外洋与陆架之间的物质和能量交换. 跨陆坡运动是近岸陆架动力过程的关键部分^[1], 并且也是近岸海洋中缺乏了解但却相对重要的物理过程^[2].

跨陆坡运动在世界各边缘海的陆架陆坡海区均有分布, 如加利福尼亚北部陆架^[3]、北卡罗莱那陆架^[4]、挪威北部陆架^[5]等, 对此国外已有许多研究.

Shearman和Lentz^[6]指出新英格兰陆架环流中沿等深线运动强于跨等深线运动, 但近表层海水的跨陆坡作用较强. Han和Loder^[7]通过模拟结合观测, 分析加拿大新斯科舍陆架水体交换及跨陆坡运动的特征. 跨陆坡运动伴随着跨陆坡输运, Dinniman和Klinck^[8]通过模拟南极绕极环流, 指出绕极底层水(CDW)存在跨陆坡输运, 并计算其热盐收支. Combes等人^[9]通过区域模拟探究阿拉斯加湾跨陆坡输运的年际及年代际变化. Vestfals等人^[10]利用模拟结果, 讨论东白令海年平均环流中跨陆坡和沿陆坡运动的季节特征及年际变化.

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中国南海北部分布着宽广的陆架陆坡结构, 陆架坡折带呈东北-西南走向. 南海北部存在3处陆架坡折辐聚带, 分别位于111°E, 115°E和119°E经线附近的陆坡上, 其海底地势十分陡峭(图1). 对于南海北部的跨陆坡运动已有初步研究, Wang等人^[11]通过观测和模式分析发现, 东沙岛附近中层环流出现很强的跨越等深线向深海运动的特征. Gan等人^[12]通过数值模拟指出, 粤东陆架海区的跨陆架输运主要由沿等深线的压强梯度的变动造成. 目前, 南海上层环流已有较清楚的认识^[13], 然而跨陆坡运动的研究还缺乏较为系统的描述, 尤其在南海北部宽广的陆坡海区, 还没有关于跨陆坡热、盐输运量的估算, 因此本文拟采用模式诊断方法对南海北部跨陆坡运动的特征进行分析.

诊断模型最初在海洋中的应用是考虑海水运动方程中主要贡献项的平衡关系, 对温盐观测数据作诊断分析^[14]. 此方法最早由Yuan等人^[15]引入国内, 并应用于东海陆架环流的研究. 近年来模型诊断方法结合了发展成熟的海洋数值模型, 如MOM^[16], TOM^[17], 最优化盒子模型^[18]和改进逆方法^[19]等. 相比于简单的动力诊断计算, 结合海洋模型的诊断计算因带有完备的动力过程而计算更加准确, 从而减少不确定性使结果更接近真实. 诊断模型能较好地估算水体输运情况^[20,21], 并能通过动量分析解析环流动力过程^[22]. POM(Princeton Ocean Model)模型在中国南海北部的诊断分析已有较为成熟的运用^[23]. 本文基于POM诊断模型, 对南海环流作诊断计算,

从气候态角度揭示南海北部跨陆坡运动的特征, 并讨论其动力过程.

1 方法与数据

1.1 诊断方法

本文基于海洋数值模式^[24], 在南海建立区域海洋诊断模型. 将已有气候态温盐数据输入诊断模型, 通过动量方程(1)和(2)及温盐诊断方程(3)和(4), 并结合连续性方程(5)及POM中自带的湍流闭合子模块^[25], 系统地诊断出南海气候态环流.

诊断方程^[26]如下:

$$\frac{\partial UD}{\partial t} + \frac{\partial U^2 D}{\partial x} + \frac{\partial UVD}{\partial y} + \frac{\partial U\omega}{\partial \sigma} - fVD + gD \frac{\partial \eta}{\partial x} + \frac{gD^2}{\rho_0} \int_{\sigma}^0 \left[\frac{\partial \rho'}{\partial x} - \frac{\sigma'}{D} \frac{\partial D}{\partial x} \frac{\partial \rho'}{\partial \sigma'} \right] d\sigma' = \frac{\partial}{\partial \sigma} \left[\frac{K_M}{D} \frac{\partial U}{\partial \sigma} \right] + F_x, \quad (1)$$

$$\frac{\partial VD}{\partial t} + \frac{\partial UVD}{\partial x} + \frac{\partial V^2 D}{\partial y} + \frac{\partial V\omega}{\partial \sigma} + fUD + gD \frac{\partial \eta}{\partial y} + \frac{gD^2}{\rho_0} \int_{\sigma}^0 \left[\frac{\partial \rho'}{\partial y} - \frac{\sigma'}{D} \frac{\partial D}{\partial y} \frac{\partial \rho'}{\partial \sigma'} \right] d\sigma' = \frac{\partial}{\partial \sigma} \left[\frac{K_M}{D} \frac{\partial V}{\partial \sigma} \right] + F_y, \quad (2)$$

$$\frac{\partial DU}{\partial x} + \frac{\partial DV}{\partial y} + \frac{\partial \omega}{\partial \sigma} + \frac{\partial \eta}{\partial t} = 0, \quad (3)$$

$$\frac{\partial TUD}{\partial x} + \frac{\partial TVD}{\partial y} + \frac{\partial T\omega}{\partial \sigma} = \frac{\partial}{\partial \sigma} \left[\frac{K_H}{D} \frac{\partial T}{\partial \sigma} \right] + F_T, \quad (4)$$

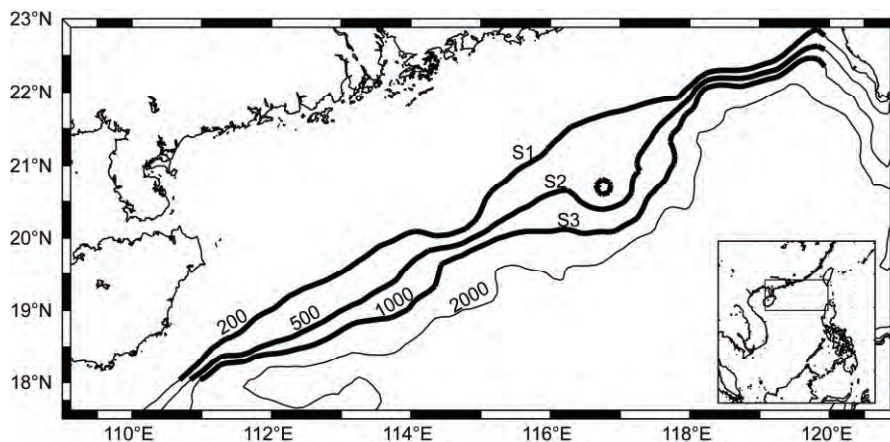


图1 南海北部陆架陆坡地形. 加粗实线分别为沿200, 500和1000 m等深线的S1, S2和S3断面

Figure 1 Bathymetry of the continental shelf in the northern South China Sea. Heavy solid lines are S1, S2, and S3 sections along isobaths 200, 500, and 1000 m, respectively

$$\frac{\partial SUD}{\partial x} + \frac{\partial SVD}{\partial y} + \frac{\partial S\omega}{\partial \sigma} = \frac{\partial}{\partial \sigma} \left[\frac{K_H}{D} \frac{\partial S}{\partial \sigma} \right] + F_s, \quad (5)$$

式中, $D \equiv H + \eta$, H 为地形深度; η 为海表高度; ρ_0 为参考密度, ρ' 为密度扰动; U 和 V 为水平速度, ω 为垂向速度; T 和 S 为温度和盐度; f 为科氏参数. K_H 和 K_M 分别为垂向运动黏性系数和垂向扩散率; F_x 和 F_y 为水平黏性, F_T 和 F_S 为水平扩散项.

1.2 诊断模型设置

诊断模型采用水平矩形正交网格($4^\circ\text{S} \sim 30^\circ\text{N}$, $99^\circ \sim 130^\circ\text{E}$, 图2(a)), 水平分辨率为 $0.1^\circ \times 0.1^\circ$. 垂向为 σ 坐标, 分32层. 地形数据采用ETOPO2($1/30^\circ$, <http://www.ngdc.noaa.gov/mgg/global/etopo2.html>), 并做适当平滑. 模型中最小水深取10 m, 最大水深取5500 m.

诊断计算所用气候态温盐数据为Generalized Digital Environment Model (GDEM-version 3.0), 水平分辨率为 $0.25^\circ \times 0.25^\circ$. 海表风应力强迫采用QuickSCAT(2000~2009年平均, http://www.ssmi.com/qscat/qscat_description.html)和NCEP(2000~2009年平均, <http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.otherflux.html>)混合风场, 水平分辨率分别为 $0.25^\circ \times 0.25^\circ$ 和 $2^\circ \times 2^\circ$. 流速和海表高度的开边界条件采用SODA v2.2.4(2000~2009年平均, <http://sodaserver.tamu.edu/>), 水平分辨率为 $0.5^\circ \times 0.5^\circ$.

sodaserver.tamu.edu/), 水平分辨率为 $0.5^\circ \times 0.5^\circ$.

诊断模型采用内外模分离积分, 内模时间步长为10 s, 外模时间步长为150 s. 模型计算是逐月分别进行, 每个月均从静止开始积分90 d, 在40 d左右达到稳定状态(图2(b)). 取诊断模型结果每月的最后5 d平均代表该月份, 进行下文分析.

1.3 诊断结果验证

本文将诊断计算结果的海表高度与AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data; <http://www.aviso.altimetry.fr/en/home.html>)卫星数据气候态的绝对动力高度进行比较验证. 海表高度能在一定程度上反映上层环流, 因此利用海表高度验证可以有效说明计算结果在海洋上层的有效性. 比较结果(图3)看出, 冬季的诊断结果与卫星数据在南海均表现为海盆尺度的气旋式环流, 这与苏纪兰^[27]和Yuan等人^[28]的观点相符. 同时, 二者均有吕宋冷涡存在于吕宋岛西侧, 且位置基本相符, 这与Qu等人^[29]的结果一致. 在夏季, 二者在南海南部均有越南暖涡存在, 这与Chi等人^[30]和

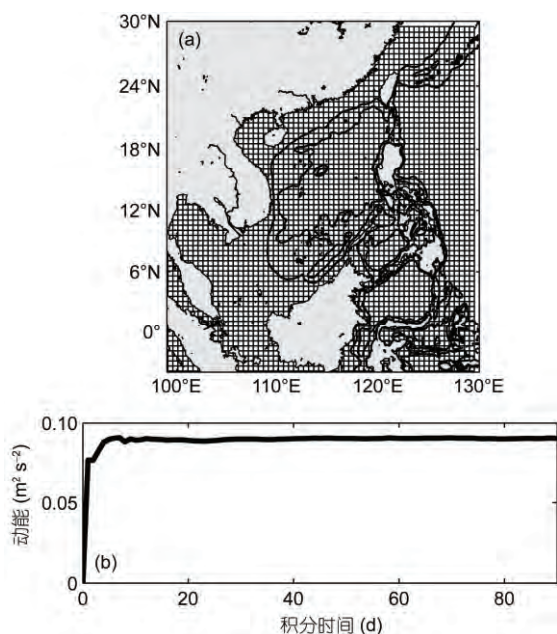


图2 诊断模型水平网格(a)及1月诊断过程体积平均动能的时间变化(b)
Figure 2 Horizontal grid of diagnostic model (a) and temporal variation of volume-averaged kinetic energy in January (b)

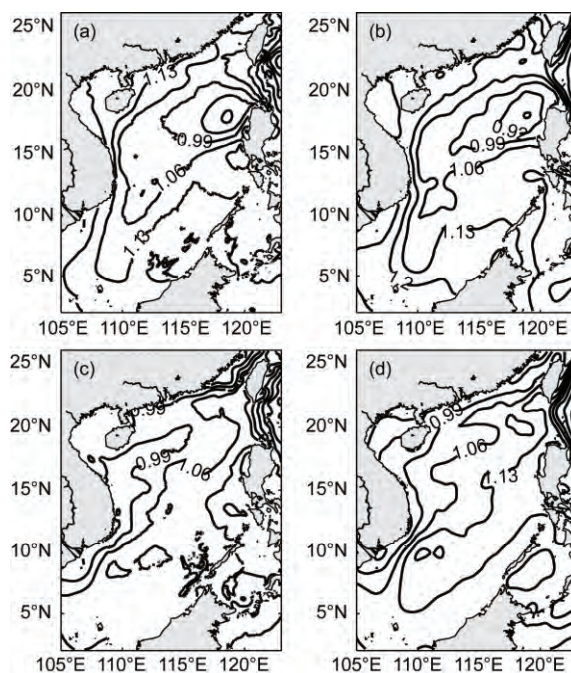


图3 诊断模型结果的海表高度与AVISO卫星数据比较(单位: m). (a) 冬季诊断结果; (b) 冬季AVISO数据; (c) 夏季诊断结果; (d) 夏季AVISO数据

Figure 3 The comparison of sea surface height (unit: m) between diagnostic result and AVISO data. (a) Diagnostic result in winter; (b) AVISO in winter; (c) diagnostic result in summer; (d) AVISO in summer

Qu^[31]的结论一致.

吕宋海峡和台湾海峡是南海北部与外界进行水交换的主要通道,其流量影响南海北部环流.且卡里马塔海峡和民都洛海峡是南海中部和南部与外界相通的主要水道,其流量影响南海水体收支.表1给出本文诊断结果的海峡年冬夏季和平均水体通量与前人结果的比较.比较可知,本文4个海峡的水体通量与前人结果较为相近.以上验证说明诊断模型结果在一定程度上再现了南海真实流场,下文利用该结果对南海北部跨陆坡运动进行分析.

2 跨陆坡运动的特征

一般认为200 m等深线以浅为陆架区,而200 m等深线至海盆之间为陆坡区.本文主要关注200~2000 m等深线之间的陆坡海区,该区等深线较为平直,但存在3处突然收紧区(分别在111°E, 115°E和119°E附近),且存在东沙岛这一地形浅滩(图1),这种地形分布容易造成局地环流异常.本文通过对气候态环流的诊断计算,分析南海北部跨陆坡运动的分布特征.定义向陆架方向的跨陆坡运动为正,向外洋

表1 南海主要海峡的年平均及冬夏季水体通量^{a)}

Table 1 Volume transport of main strait in the South China Sea in annual mean, winter, and summer

方法	吕宋海峡	台湾海峡	卡里马塔海峡	民都洛海峡	参考文献
GDEM, POM诊断模型	-4.84	2.30	1.01	0.80	本文
锚定船测		2.0			Fang等人 ^[32]
GDEM, P矢量方法	-6.5				Chu和Li ^[33]
绕岛理论	-4.2				Qu等人 ^[34]
OGCM			4.4±0.5	1.9±1.5	Lebedev和Yaremchuk ^[35]
NLOM	-1.8±1.0	0.7±0.3			Metzger和Hurlburt ^[36]
历史资料	-4.2~5.0				Su ^[37]
诊断方法	-3				Yaremchuk和Qu ^[38]
MOM2.0	-6.4	1.2	3.15	0.25	Fang等人 ^[39]
	-4.37	0.45	1.32	1.77	Fang ^[40]
全球模式	-10.2	2.0			Song ^[41]
区域模式		1.0	1.8	0.69	Yu ^[42]
POM	-5.7				Zhao等人 ^[43]
	-4.0±5.1	2.7			Hsin等人 ^[44]
潜标观测	-2.8				Zhang等人 ^[45]
GDEM, POM诊断模型	-6.06	1.56	1.82	5.92	本文
GDEM, P矢量方法	-13.7(Feb)				Chu和Li ^[33]
诊断方法	-4.8				Yaremchuk和Qu ^[38]
MOM2.0	-11.16	0.09	7.01	0.45	Fang等人 ^[39]
	-7.47	-0.65	4.0	2.98	Fang ^[40]
全球模式	-12.2				Song ^[41]
4.5层模式		0.26	2.9	1.1	Yu ^[42]
POM	-8.1				Zhao等人 ^[43]
潜标观测	-4.7				Zhang等人 ^[45]
WOA13, POM诊断模型	-3.68	3.21	-0.32	0.02	本文
诊断方法	-1.2				Yaremchuk和Qu ^[38]
MOM2.0	-2.31	2.54	-1.36	0.18	Fang等人 ^[39]
	-1.86	1.88	-1.3	0.78	Fang ^[40]
全球模式	-8.2				Song ^[41]
4.5层模式		1.4	0.1	-0.1	Yu ^[42]
POM	-1.0				Zhao等人 ^[43]
潜标观测	-0.5				Zhang等人 ^[45]

a) 4个海峡通量均为流出南海为正、流入南海为负

方向的跨陆坡运动为负。

2.1 跨陆坡运动的水平分布

南海北部垂向平均流场沿地形梯度方向的运动分量,即跨陆坡运动,其在200~2000 m等深线之间水平分布如图4(a)和(b)所示。在南海陆坡区域有较为明显的跨陆坡运动存在,且随等深线的变化而分布不均匀。冬季在陆坡海区具有较强的跨陆坡运动,且主要为向陆架方向,分布于114°E以西的200~500 m等深线之间区域、东沙岛以东附近区域;而向外洋方向的跨陆坡运动,主要分布在东沙岛以西附近区域及1000~2000 m等深线之间的部分区域。夏季的跨陆坡运动较弱,其中东沙岛附近维持相对较强的跨陆坡运动,另外,在111°,115°和119°E的陆坡区域由于海底地形复杂也分布着向陆架方向的跨陆坡运动。相比而言,夏季的跨陆坡运动强度小于冬季,且向外洋方向的运动区域相对扩大。跨陆坡运动在水平方向上不均匀分布,且强值区主要表现在东沙岛

附近和等深线收紧的地形复杂区域。

2.2 跨陆坡运动的垂向分布

为分析跨陆坡运动的垂向分布,本文分别沿200, 500和1000 m等深线取3个不规则垂向断面S1, S2和S3,如图1所示。其中,S1断面靠近浅海陆架,S3断面远离陆架靠近外洋。

S1断面的跨陆坡运动分布如图5(a)和(d)所示,跨陆坡运动主要为正,且存在3处强值中心,分别位于111°,115°及119°E附近;负的跨陆坡运动范围小且运动较弱。冬季跨陆坡运动强度较大,最大速度达到 0.2 m s^{-1} 以上,位于115°和119°E附近。而夏季跨陆坡运动明显减弱尤其在强值中心,但强值中心位置仍维持不变。S2断面上的跨陆坡运动分布如图5(b)和(e)所示,冬季仍存在上述115°和119°E附近的强值中心,但强度有所减弱,另外一个强值中心出现在112°~113°E之间;夏季的强值中心较为分散,且强度削弱更加明显。S3断面上的跨陆坡运动分布如图5(c)

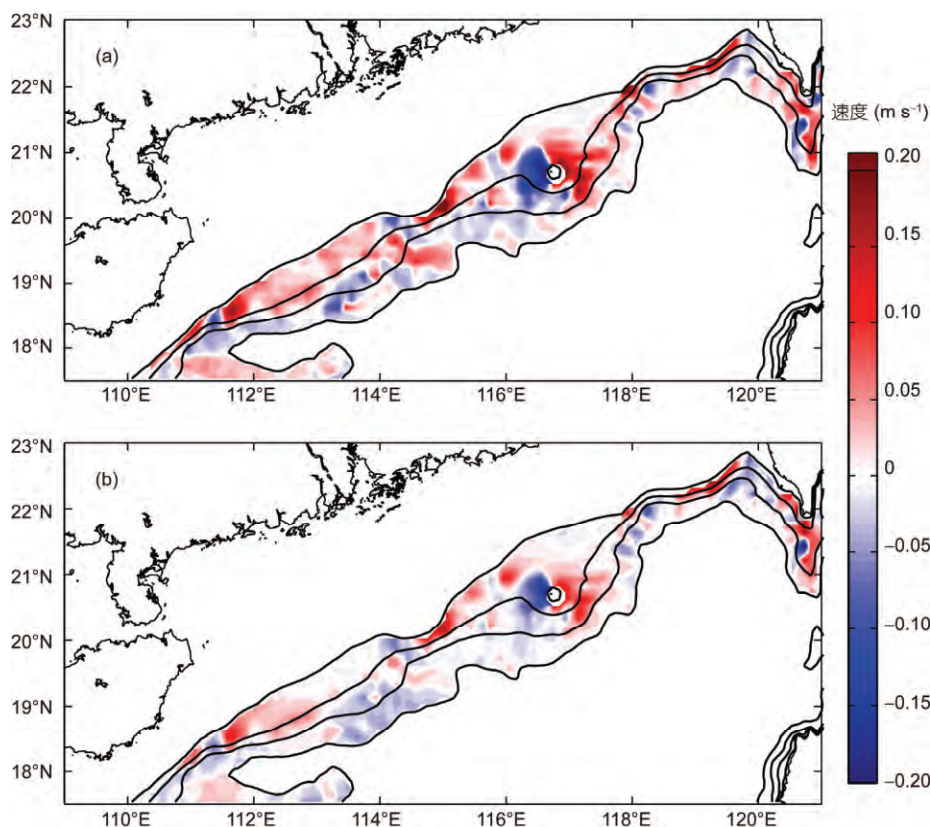


图4 南海北部垂向平均流场的跨陆坡运动分量在冬季(a)和夏季(b)的分布。暖色代表向陆架方向,冷色代表向外洋方向

Figure 4 Cross-shelf flow of vertical averaged flow in winter and summer in the northern South China Sea. Warm color stands for on-shelf flow and cold color for off-shelf flow

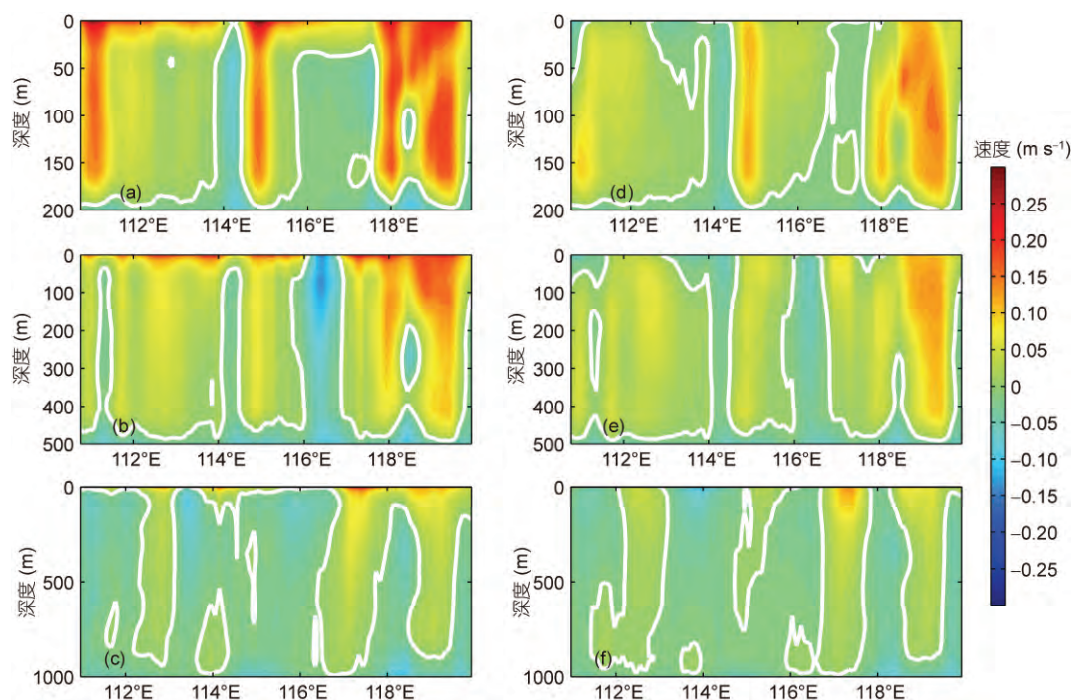


图5 跨陆坡运动速度的断面分布. 暖色为向陆架方向, 冷色为向外洋方向, 白线为流速零值. (a)~(c) 冬季; (d)~(f) 夏季; (a), (d) S1断面; (b), (e) S2断面; (c), (f) S3断面

Figure 5 Cross-section velocity distribution of cross-shelf flow. (a)~(c) Winter; (d)~(f) summer; (a), (d) section S1; (b), (e) section S2, (c), (f) section S3. Warm color stands for on-shelf flow, cold color stands for off-shelf flow, white lines stand for velocity of zero

和(d)所示, 负的跨陆坡运动范围扩大, 上述3处强值中心被正负速度交替分布代替, 且深层运动较弱. 三处断面的跨陆坡运动强值区对跨陆坡水体输运起到主要贡献. 垂向断面上看, 跨陆坡运动也存在较好的正压性.

2.3 跨陆坡输运

根据跨陆坡运动的速度, 计算S1, S2和S3断面的水体输运, 并进一步估算其热盐输运. 计算采用以下公式^[39]:

$$F_v = \sum_i \left[\Delta l_i \sum_k v_{i,k} \Delta z_k \right], \quad (6)$$

$$F_H = c_p \sum_i \left[\Delta l_i \sum_k T_{i,k} \rho_{i,k} v_{i,k} \Delta z_k \right], \quad (7)$$

$$F_s = \sum_i \left[\Delta l_i \sum_k S_{i,k} \rho_{i,k} v_{i,k} \Delta z_k \right] \times 10^{-3}, \quad (8)$$

其中, F_v 为体积输运量, F_H 为热含量输运量, F_s 为盐含量输运量, v 为断面速度, Δl_i 和 Δz_k 分别为水平距离和垂向距离, c_p 为定压比热, ρ 为海水密度, T 和 S 分别为温度和盐度.

表2列出上述3处断面年平均及冬夏季的体积输运和热盐含量输运情况. S1和S2断面的输运量均为正, 即这两处断面的体积输运、热盐含量输运均表现为向陆架方向, 而断面S3的输运情况相反, 为向外洋方向. 量值上, S1和S2断面的输运量较大, S3断面的输运量较小. 并且, S1和S2断面的输运量存在冬季强、夏季弱的季节特征, 而S3断面季节差别不明显. 因此, 在200~500 m等深线之间海区, 跨陆坡运动携带大量海水同时伴随着大量热盐向陆架方向输送, 而500~2000 m以深陆坡海区跨陆坡输运为向外洋方向.

根据S1和S2断面的体积输运可知, 在沿陆坡方向上二者之间存在较强的水体辐聚, 这是由于西边海水流出大于东边流入, 导致大量深海海水向较浅的陆坡区补充; 同样, S2和S3断面的体积输运量说明在二者之间存在较强的水体辐散, 这是由于东边海水流入大于西边流出, 导致这两处断面之间水体堆积, 从而向两侧辐散.

3 动量与涡度平衡分析

南海北部陆坡环流主要沿等深线运动, 但由于

表 2 S1, S2 和S3 断面的年平均及冬夏季的输运情况^{a)}

Table 2 Transport through sections S1, S2 and S3 in annual mean, winter, and summer

断面	年平均			冬季			夏季		
	体积输运 (Sv)	热含量输运 (PW)	盐含量输运 (Gg s ⁻¹)	体积输运 (Sv)	热含量输运 (PW)	盐含量输运 (Gg s ⁻¹)	体积输运 (Sv)	热含量输运 (PW)	盐含量输运 (Gg s ⁻¹)
S1	9.4593	0.7826	342.5291	12.9505	1.0644	468.8330	8.6024	0.7261	311.2420
S2	15.8322	0.8459	574.9761	20.3340	1.0595	738.1627	15.8991	0.8595	577.5290
S3	-2.1246	-0.2222	-76.0133	-2.3324	-0.1604	-83.4106	-2.5065	-0.2782	-89.6832

a) 1 Sv=10⁶ m³ s⁻¹, 1 PW=10¹⁵ W, 1 Gg s⁻¹=10⁶ kg s⁻¹

流动的不稳定性等因素造成局地环流异常。Song和Chao^[46]在加利福尼亚中部陆架环流的研究中也指出,地形变化影响跨陆坡运动和沿陆坡运动。南海北部结构独特的陆坡地形,造成跨陆坡运动的特殊分布。下文选取冬季S2断面为例,讨论跨陆坡运动的动力过程。

比较沿陆坡运动和跨陆坡运动可知,沿陆坡运动速度远大于跨陆坡运动,且沿陆坡运动速度大约

是跨陆坡运动速度的4~6倍。说明南海北部陆坡流以沿陆坡运动为主,跨陆坡运动相对沿陆坡运动较弱,且跨陆坡运动分量占15%~20%。

选取冬季S2断面进行动量平衡分析^[47],动量平衡方程中压强梯度力项、科氏力项、对流和扩散项占主要成分,其分布如图6所示;而海表风应力项和海底摩擦力项相比前者小2个量级,因而图中未给出。陆坡海区环流主要受地转平衡支配,海水运动主要

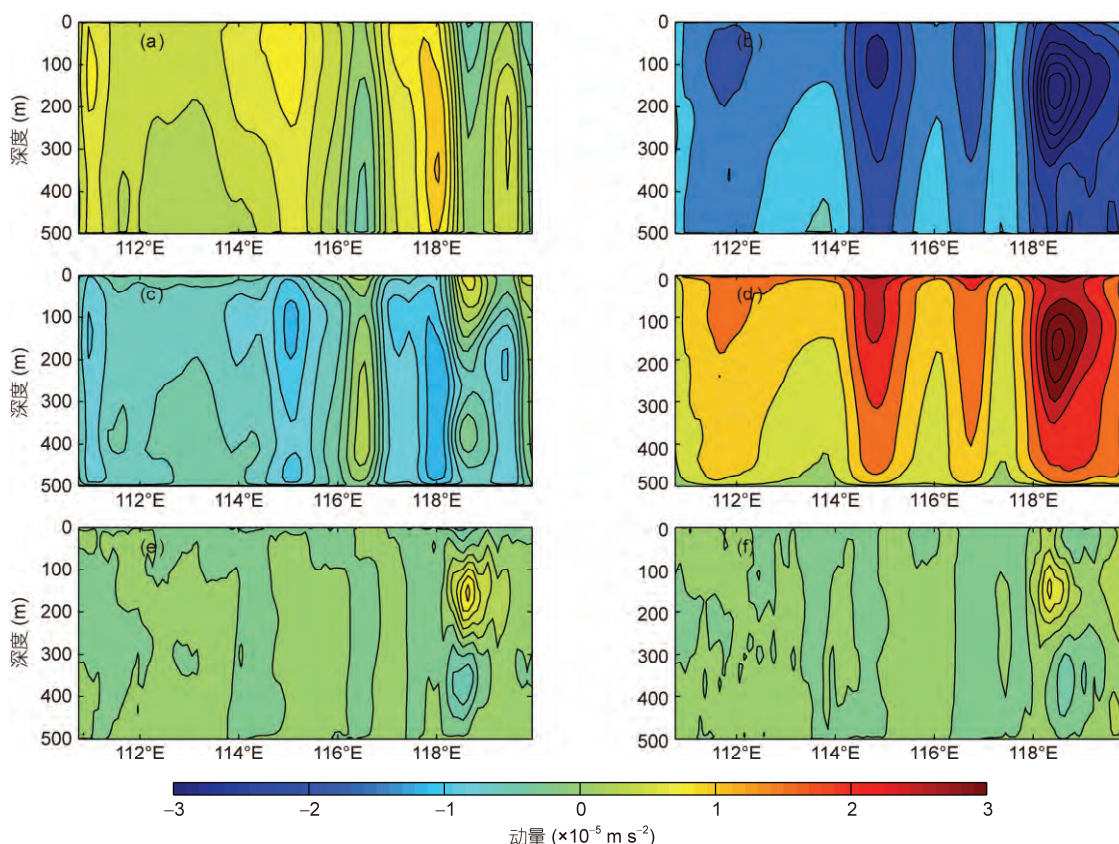


图 6 冬季S2断面上动量平衡方程中各项的垂向分布。(a) x方向压力梯度力项;(b) y方向压力梯度力项;(c) x方向科氏力项;(d) y方向科氏力项;(e) x方向对流和扩散项;(f) y方向对流和扩散项

Figure 6 Terms of momentum balance equation in section S2 in winter. (a) Pressure gradient force in x direction; (b) pressure gradient force in y direction; (c) Coriolis force in x direction; (d) Coriolis force in y direction; (e) diffuse and advection in x direction; (f) diffuse and advection in y direction

受压强梯度力和科氏力控制. S2断面上, x 和 y 方向的压力梯度力项和科氏力项主导动量平衡, 且在整个垂直方向上表现出局部地区的正压性. 并且, 在118°E以东区域动量平衡中的压强梯度力项和科氏力项量值较大, 说明该区域海水具有较大动能, 也表现出较强的跨陆坡运动. 对流与扩散项在垂向分层结构, 也说明该区域海水的斜压性较为明显.

通过分析正压涡度平衡方程, 讨论其与跨陆坡运动的关系. 正压涡度平衡方程^[11,48]如下:

$$\frac{\partial}{\partial t} \left[\frac{\partial}{\partial x} \left(\frac{\bar{v}}{D} \right) - \frac{\partial}{\partial y} \left(\frac{\bar{u}}{D} \right) \right] = - \left[\bar{u} \frac{\partial}{\partial x} \left(\frac{f}{D} \right) + \bar{v} \frac{\partial}{\partial y} \left(\frac{f}{D} \right) \right] + J \left(\Phi, \frac{1}{D} \right) + \text{curl} \left(\frac{F}{D} \right) - \text{curl} \left(\frac{A}{D} \right) + \text{curl} \left(\frac{\tau_a}{\rho_0 D} \right) - \text{curl} \left(\frac{\tau_b}{\rho_0 D} \right), \quad (9)$$

式中, $\frac{\partial}{\partial t} \left[\frac{\partial}{\partial x} \left(\frac{\bar{v}}{D} \right) - \frac{\partial}{\partial y} \left(\frac{\bar{u}}{D} \right) \right]$ 为趋势项; $- \left[\bar{u} \frac{\partial}{\partial x} \left(\frac{f}{D} \right) + \bar{v} \frac{\partial}{\partial y} \left(\frac{f}{D} \right) \right]$ 为地转位势涡度平流项(advection of the geostrophic potential vorticity, APV); $J \left(\Phi, \frac{1}{D} \right)$ 为地形

与斜压联合效应项 (joint effect of baroclinicity and bottom relief, JEBAR), 其中位势能量 $\Phi = \int_{-H}^{\eta} z g \rho / \rho_0 dz$;

$\text{curl} \left(\frac{F}{D} \right)$ 为平流项(advection, ADV); $\text{curl} \left(\frac{A}{D} \right)$ 为扩散项(diffusion, DIF); $\text{curl} \left(\frac{\tau_a}{\rho_0 D} \right)$ 为海表风应力项; $\text{curl} \left(\frac{\tau_b}{\rho_0 D} \right)$ 为海底摩擦力项.

涡度平衡方程中, JEBAR, APV, 平流和扩散项为主要贡献项, 而海表风应力旋度项和海底摩擦力旋度项为小量. 其中, 前3项在S2断面上冬季的分布如图7(a)所示. 冬季S2断面表现出较强的跨陆坡运动, 向陆架方向较强的运动主要发生在113°E, 115°E, 118°E和119°E经线上的陆坡区域, 而向外洋的跨陆坡运动主要发生于116°~117°E之间. 断面S2冬季跨陆坡运动速度的垂向平均如图7(b)所示, 较好地体现该断面的跨陆坡运动特征. 比较图7(a)和(b)可知, 较强的跨陆坡运动区域受控于JEBAR和APV. JEBAR的变化由密度场决定, 而APV的变化与流场相关^[49]. 因此JEBAR体现密度斜压场与海底地形的相互作用; APV则体现的是跨陆坡运动产生的位势涡度平流以

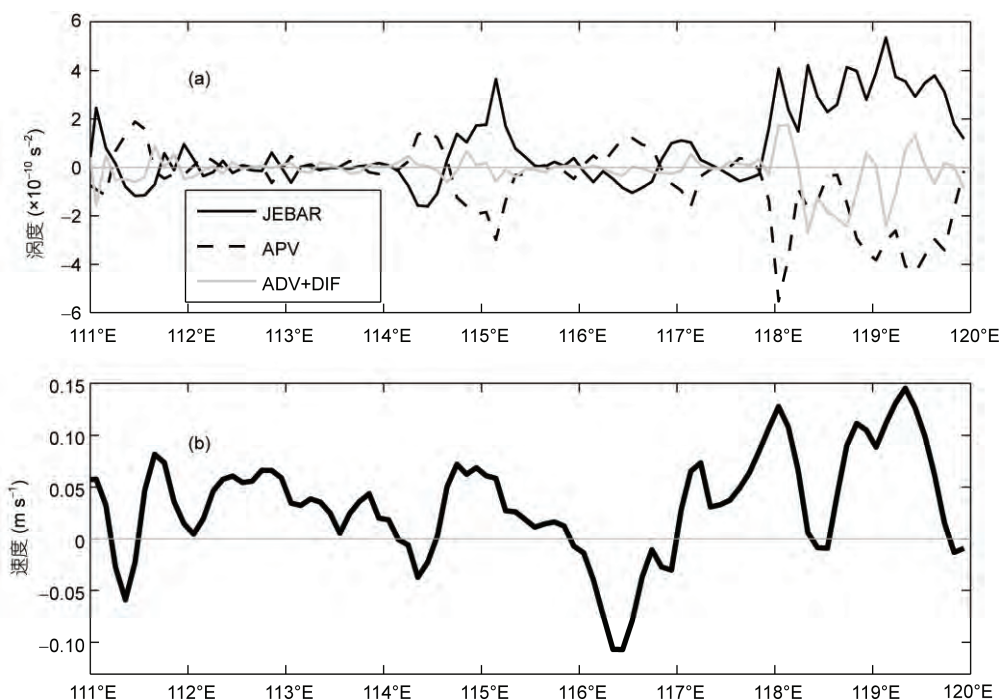


图7 冬季S2断面上正压涡度平衡方程中各项(a)与跨陆坡运动速度的垂向平均(b)

Figure 7 Terms of barotropic vorticity balance equation (a) and vertical averaged velocity of cross-shelf flow (b) in section S2 in winter

达到涡度守恒. 在118°E以东区域, 由于黑潮水入侵南海且与陆坡地形相互作用产生较强的斜压结构, 导致强的JEBAR分布, 从而引起较强跨陆坡运动的发生.

4 结论

本文利用GDEM气候态温盐数据对南海环流作诊断计算, 从气候态流场结果揭示南海北部跨陆坡运动的空间特征、输运情况及动力机制. 得到以下结论.

南海北部普遍分布着陆坡运动且空间特征明显. 水平结构上, 200~500 m等深线之间的陆坡海区跨陆坡运动较强, 而500~2000 m等深线之间海区跨陆坡运动较弱, 且强运动区还分布在东沙岛附近及等深线收紧区等地形复杂处. 垂向结构上, 沿200和500 m等深线断面存在3处较强的向陆架的跨陆坡运动中心, 且冬季最强跨陆坡运动速度可达 0.2 cm s^{-1} ; 沿1000 m等深线断面的跨陆坡运动较弱, 且向外洋方向的运动范围扩大, 大值中心较为分散.

跨陆坡运动引起近岸陆架与外洋海水之间的交换, 跨陆坡输运的空间分布也有较明显的特征. 沿200和500 m等深线断面主要为向陆架方向的体积输运, 年平均值分别为9.4593和15.8322 Sv; 而沿1000

m等深线断面主要为向外洋方向的体积输运, 年平均值为 -2.1246 Sv . 热盐输运上, 跨陆坡运动携带大量热量和盐分流向近岸陆架, 沿200和500 m等深线断面年平均热含量和盐含量的输运分别为0.7826 0.8459 PW和342.5291, 574.9761 Gg s^{-1} , 这体现了跨陆坡运动对近岸陆架有热盐补充的输运特征; 而沿1000 m等深线断面热、盐含量输运分别为 -0.2222 PW 和 $-76.0133 \text{ Gg s}^{-1}$. 沿200和500 m等深线断面输运存在冬强夏弱的季节差异, 而1000 m等深线断面季节特征不明显. 不同断面东西两侧水体流入流出的不平衡, 导致沿200和500 m等深线断面之间存在较强的水体辐聚, 而沿500和1000 m等深线断面之间存在较强的水体辐散, 因而促使跨陆坡水体输运的发生.

南海北部陆坡流中沿陆坡运动虽占主要成分, 但跨陆坡运动也不容忽视, 占15%~20%. 陆坡流动由地转平衡占主导作用, 且跨陆坡运动在垂向上具有明显的正压性, 而118°E以东表现为一定的斜压性. 正压涡度平衡方程逐项分析发现, 地形与斜压联合效应项、位势涡度平流项、对流和扩散项是跨陆坡运动的主要贡献项. 因此, 地形与斜压的相互作用是跨陆坡运动产生的主要影响因素, 且在118°E以东区域受黑潮入侵影响使斜压效应更强, 对跨陆坡运动的增强作用更加显著.

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Summary for “南海北部跨陆坡运动的模式诊断分析”

Model diagnostic analysis of cross-shelf flow in the northern South China Sea

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To explore cross-shelf flow in the northern South China Sea, model diagnostic calculation was conducted using a regional, three-dimensional, primitive equation model (POM) and the climatological temperature and salinity fields supplied by the Generalized Digital Environment Model (version 3.0). Using the model calculations, we systematically evaluated the characteristics of cross-shelf flow and estimated its volume, heat, and salt transports in different sections along the continental slope. The dynamic process of cross-shelf flow was further analyzed using the vorticity balance.

Results revealed the spatial distribution of the cross-shelf flow in the northern South China Sea. Between the 200–2000 m isobaths, the horizontal distribution of cross-shelf flow was uniform, and strong cross-shelf flow was present in areas of the continental slope with complex topography. We selected three sections (S1, S2, and S3 along the 200, 500, and 1000 m isobaths, respectively) to characterize the cross-shelf flow. Three local maximal cross-shelf velocities in the on-shelf direction were detected in sections S1 and S2, but this feature was not clear in section S3. Strong cross-shelf flow (>2 cm/s) was present at about 115°E and 118°E of section S1 in winter. The annual mean cross-shelf volume transports in sections S1, S2, and S3 were 9.4, 15.8, and -2.1 Sv, respectively. The heat content transports were 0.78, 0.84, and -0.22 PW, respectively, and the salt content transports were 342.5, 575.0, and -76.0 Gg s^{-1} , respectively. The cross-shelf flow was towards the shelf in the 200–500 m isobaths region and in the opposite direction in the 500–2000 m isobaths region. Cross-shelf transport was stronger in winter and weaker in summer in sections S1 and S2, but no seasonal difference was found in section S3. These cross-shelf transports of sea water, heat, and salt along the continental shelf reflect the main characteristics of cross-shelf flow.

According to the volume transport between the three sections, flow convergence arose between sections S1 and S2 and divergence occurred between sections S2 and S3. In terms of volume conservation, these spatial distributions of flow convergence and divergence resulted in the cross-shelf flow. The along-shelf flow was the primary component of slope current, whereas cross-shelf flow contributed only about 15%–20%. Although cross-shelf flow was not as strong as along-shelf flow, its influence must not be ignored due to its huge volume, heat, and salt transports. Analysis of momentum balance revealed that the slope current was mainly controlled by the geostrophic equilibrium, in which the pressure gradient and Coriolis force played a dominated role. The cross-shelf flow was mainly barotropic in most regions, but it exhibited a baroclinic feature in the region east of 118°E . The analysis of barotropic vorticity balance indicated that the cross-shelf flow was mainly controlled by the joint effect of baroclinicity and bottom relief term (JEBAR), advection of the geostrophic potential vorticity term (APV), and the advection and diffusion term. The JEBAR term mainly controlled the cross-shelf flow along the continental slope due to the positive potential vorticity produced by the interaction between the baroclinic sea water and topography. To the east of 118°E , the intrusive Kuroshio Current led to interaction between baroclinic sea water and the continental slope, which increased the JEBAR term and therefore strengthened the cross-shelf flow.

South China Sea, diagnostic model, cross-shelf flow, transport, vorticity balance

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